

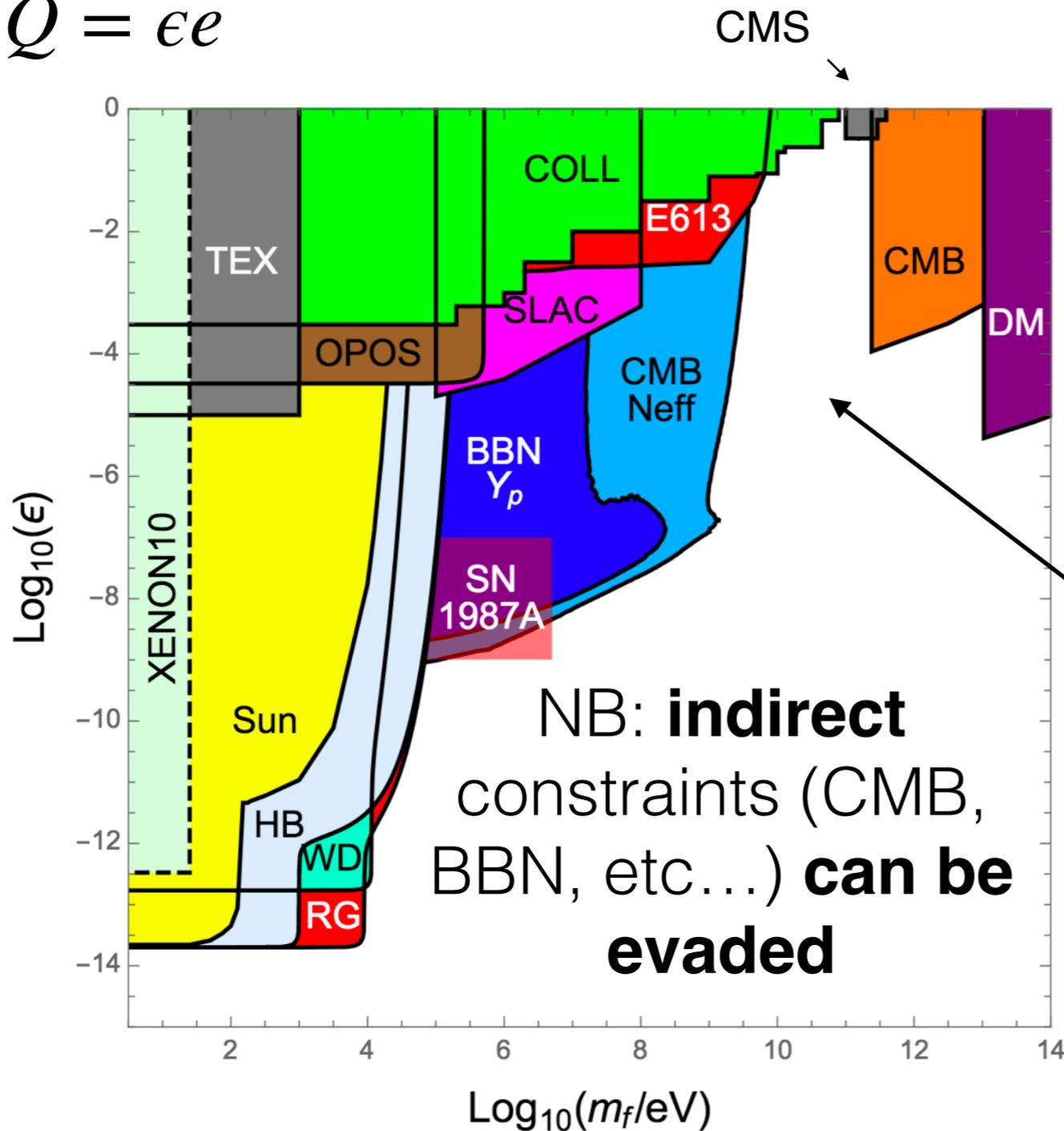
Search for millicharged particles at the LHC with the **milliQan prototype**

Matthew Citron

Paper to be published in PRD:
[arXiv:2005.06518](https://arxiv.org/abs/2005.06518)

Many ways to search for mCP*

$$Q = \epsilon e$$



Searches using colliders, effects on sun, stars and supernovae, cosmological bounds, ... cover wide range in masses/charges

but

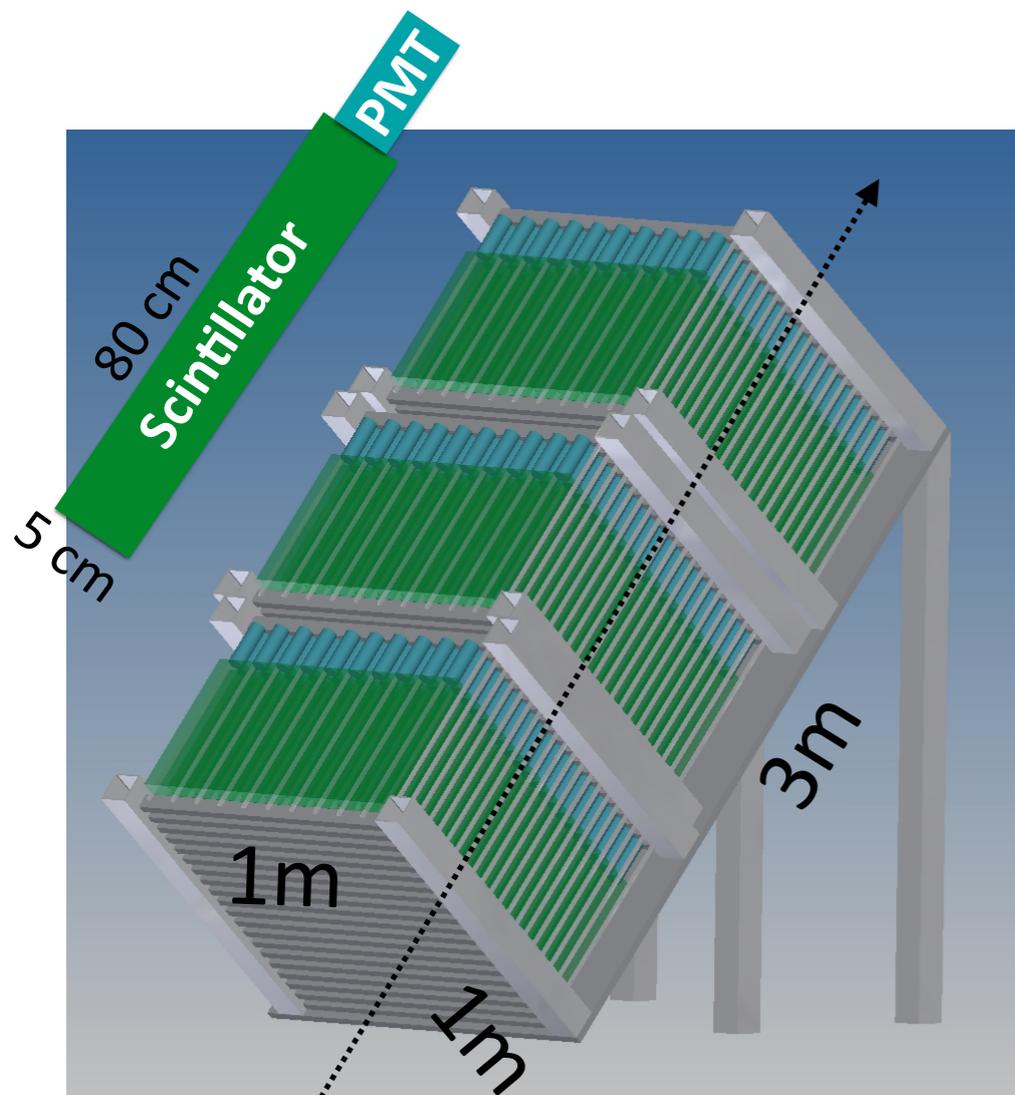
big gap for heavier (\sim GeV) low charged particles

target with **milliQan** at the LHC!

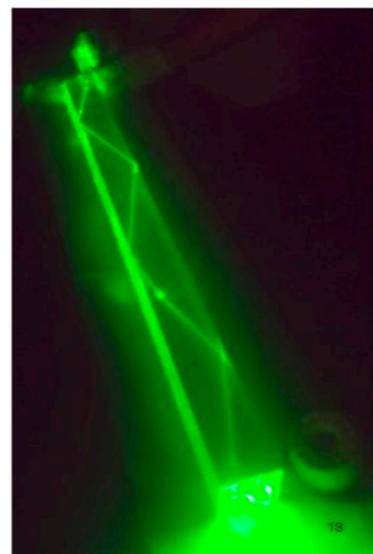
[arXiv:1511.01122](https://arxiv.org/abs/1511.01122)

milliQan detector concept

Initial design in 2016 LOI: 1200 scintillating bars in three layers (400 pointing paths)



PMT



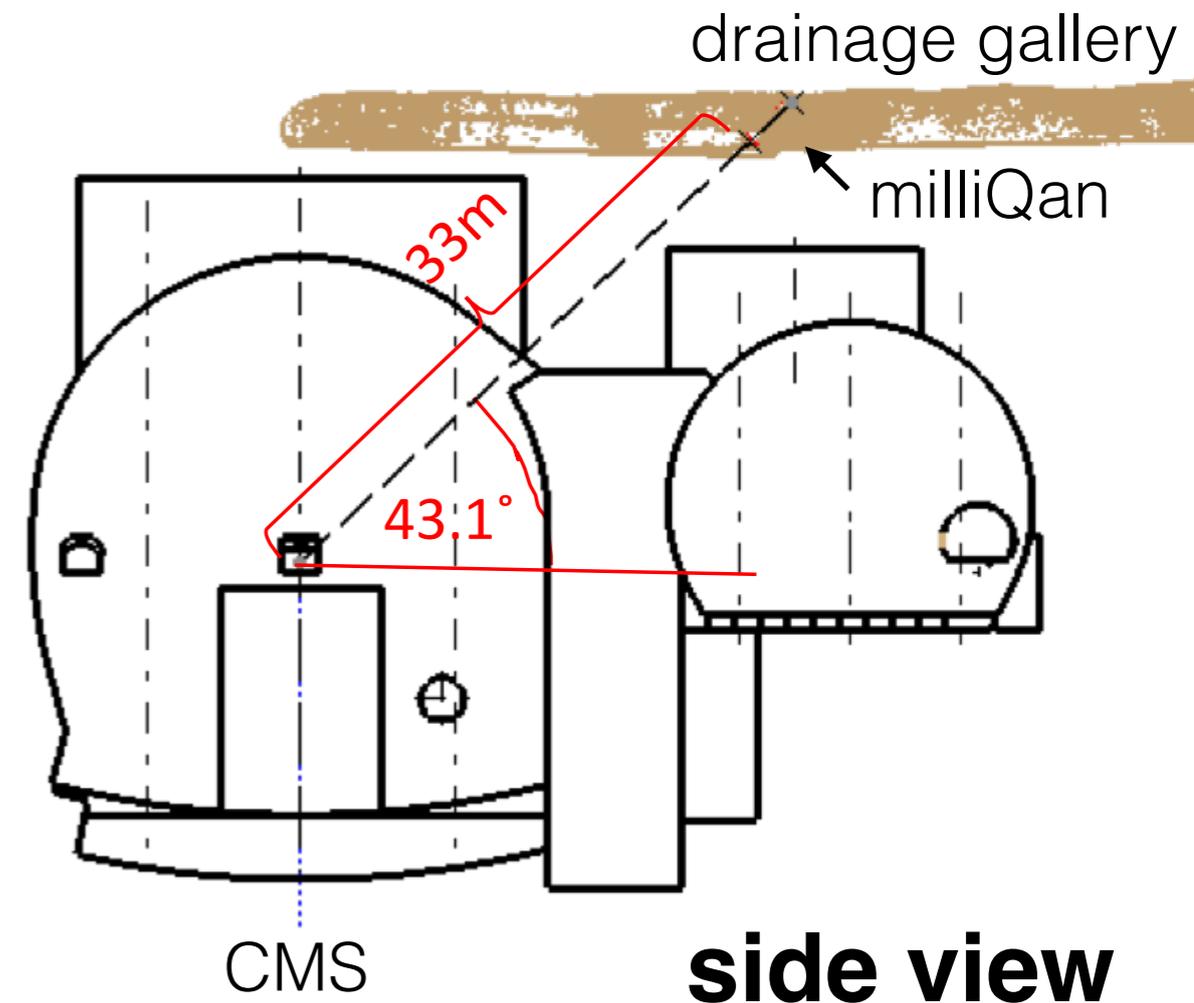
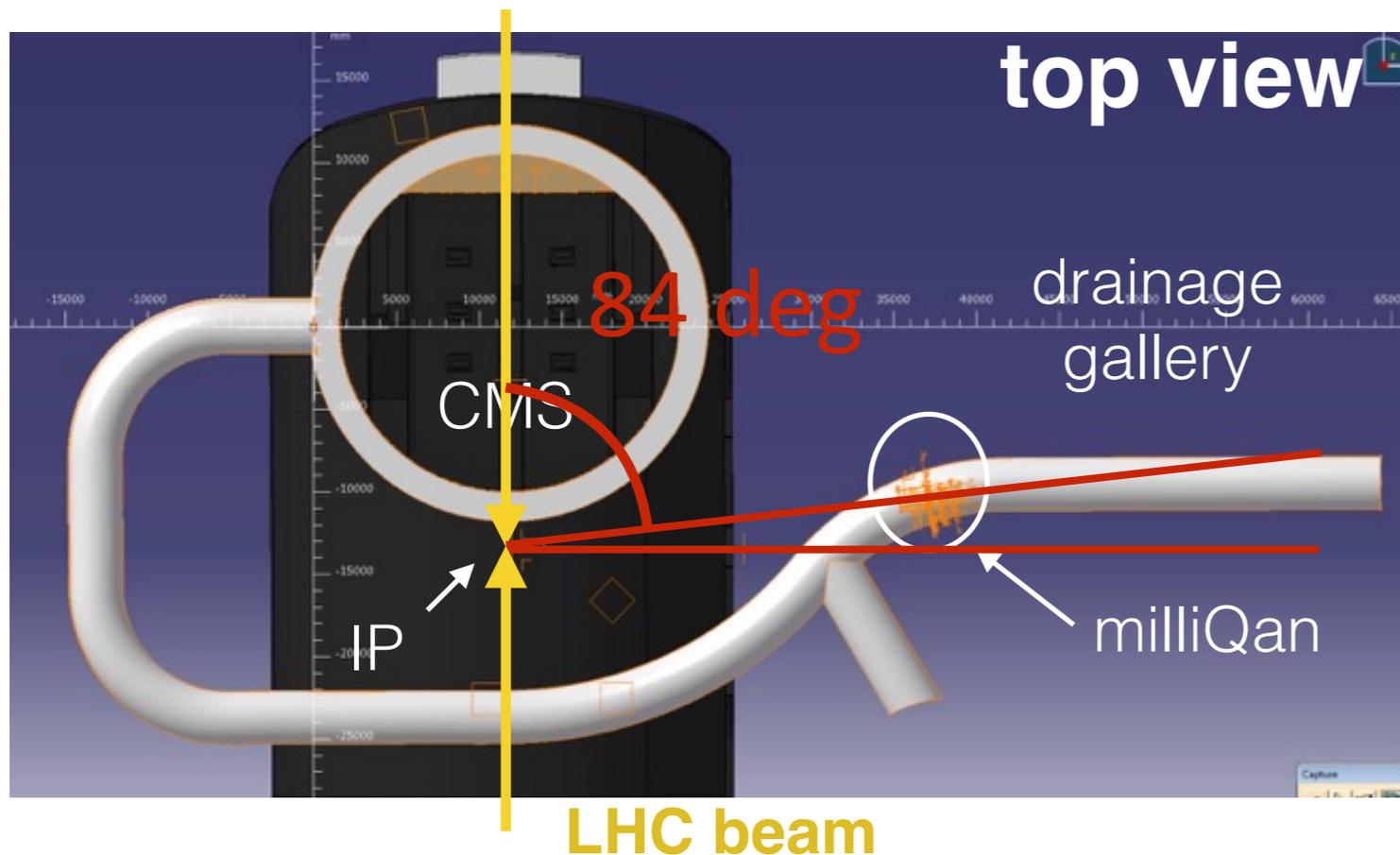
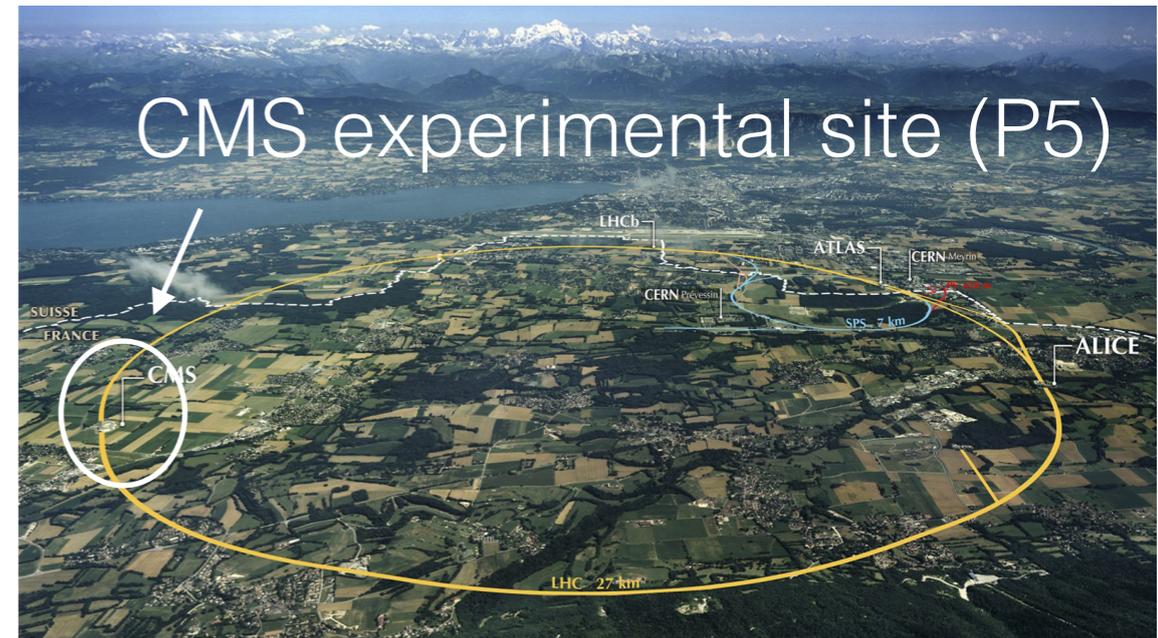
Scintillator bar

- **Key idea:** use scintillator bar array to detect (very) small ionisation from low charged particles
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small (~ 15 ns) time window and that points towards the IP
- Modular design is easy to scale and adapt!



Location

- Place detector in CMS experimental site within existing 'drainage gallery'
- Location 33 m from interaction point (including 17 m rock) → beam particles greatly suppressed



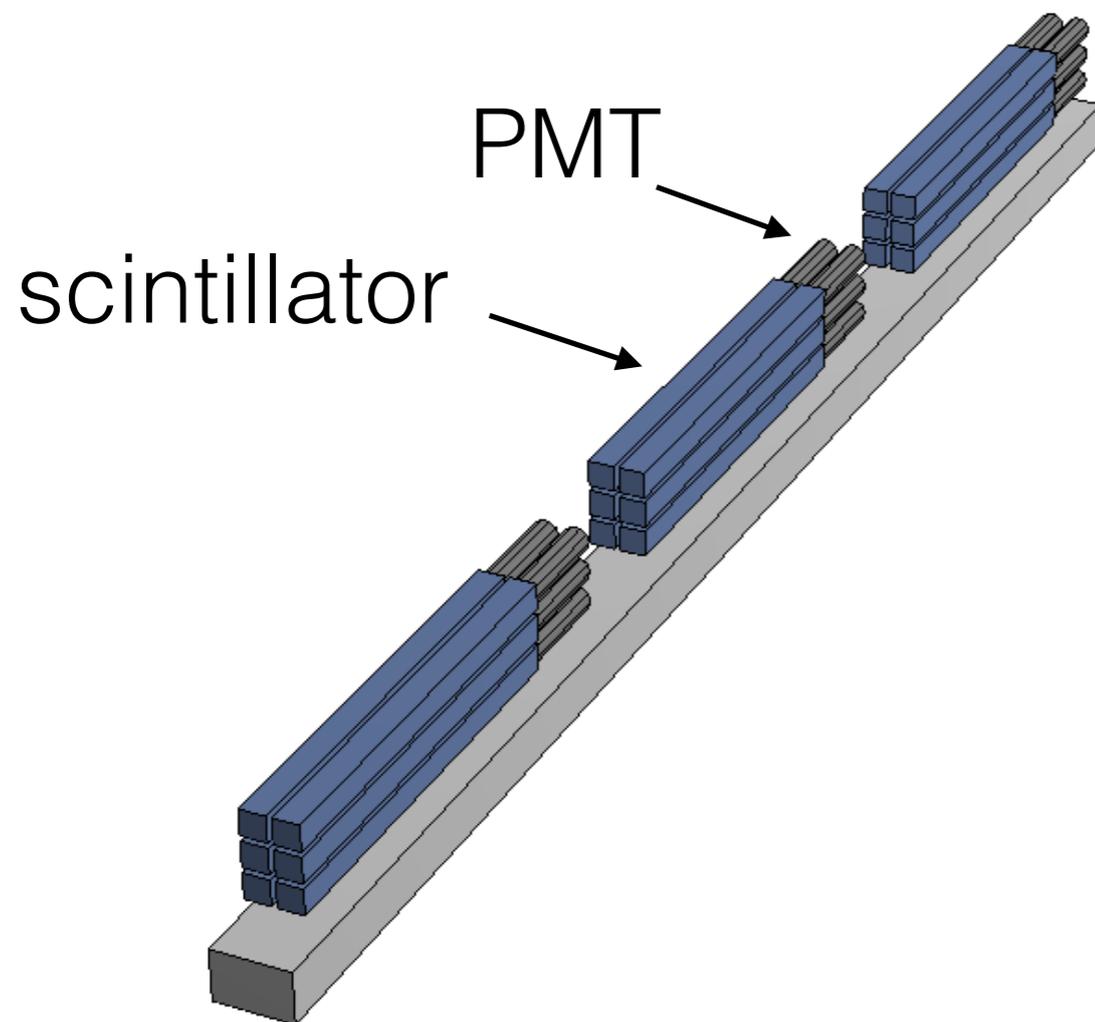
Location

2.78m high
2.73m wide



Sept 2017: milliQan demonstrator installed to **study backgrounds** and **prove feasibility** of the experiment!

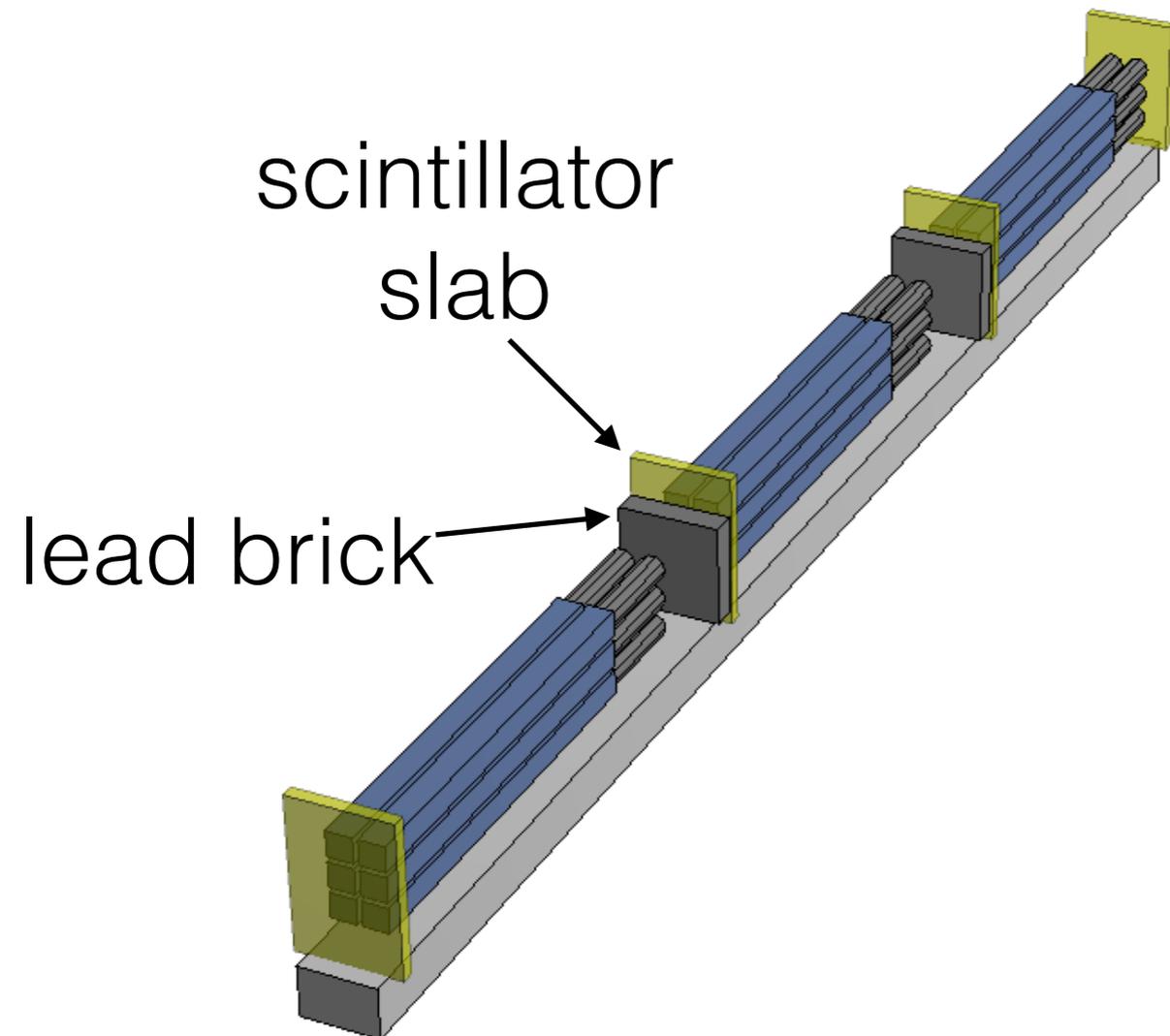
Demonstrator components



- 3 layers of 2x3 scintillator+PMT
 - ~ 1% prototype of full milliQan detector



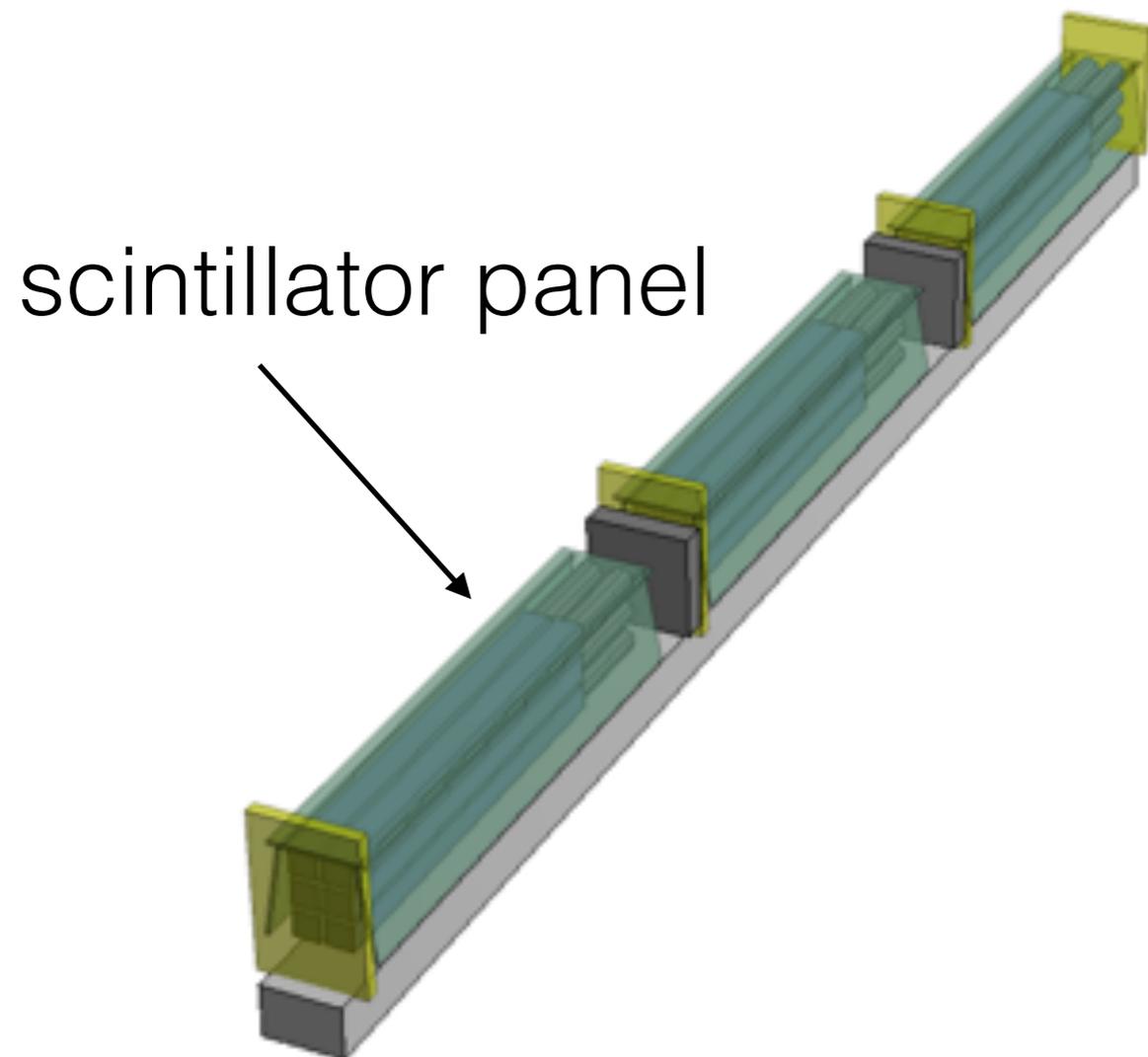
Demonstrator components



- 3 layers of 2x3 scintillator+PMT
 - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
 - Tag thru-going particles, shield radiation



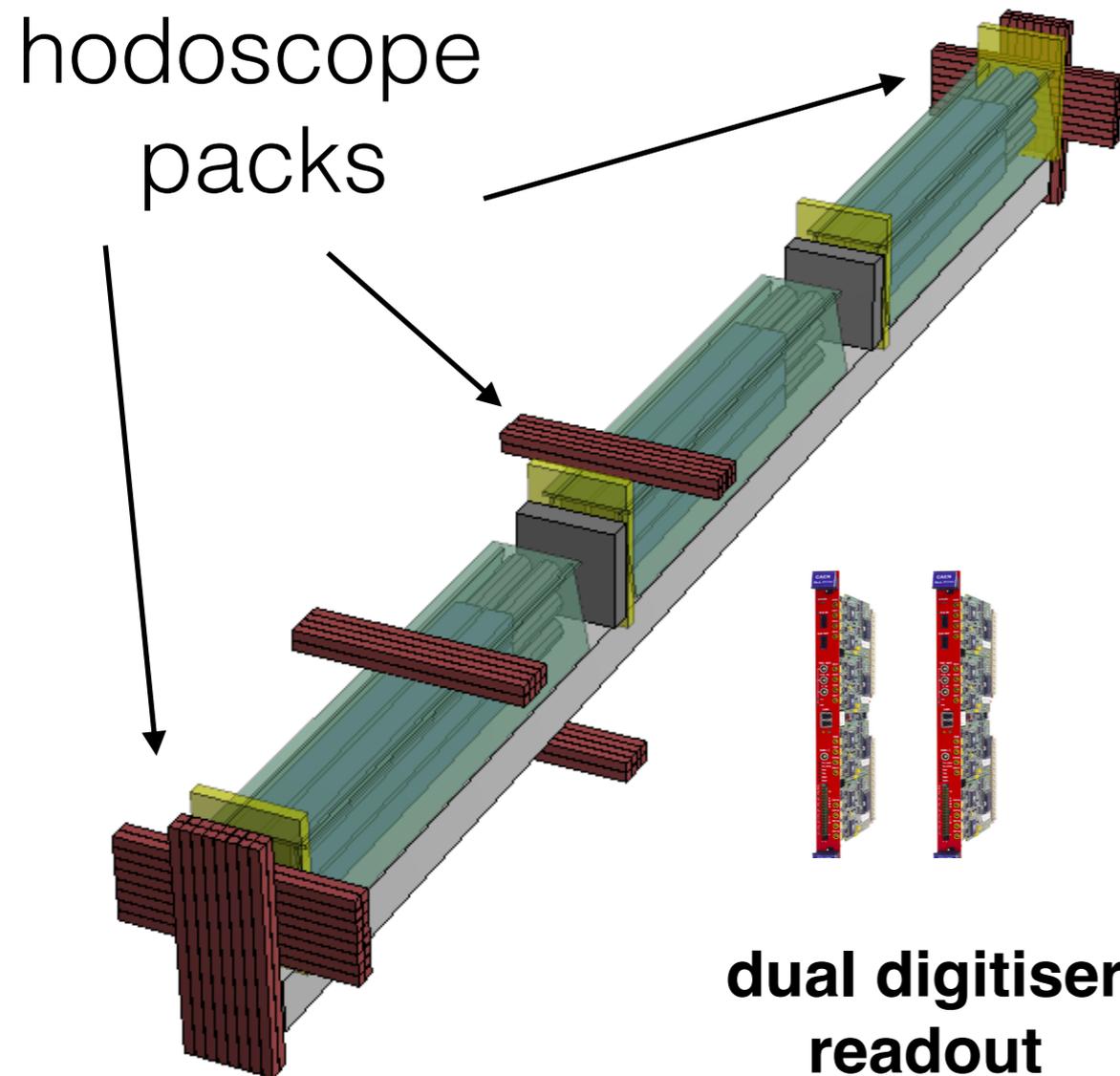
Demonstrator components



- 3 layers of 2x3 scintillator+PMT
 - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
 - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
 - Tag cosmic muons



Demonstrator components



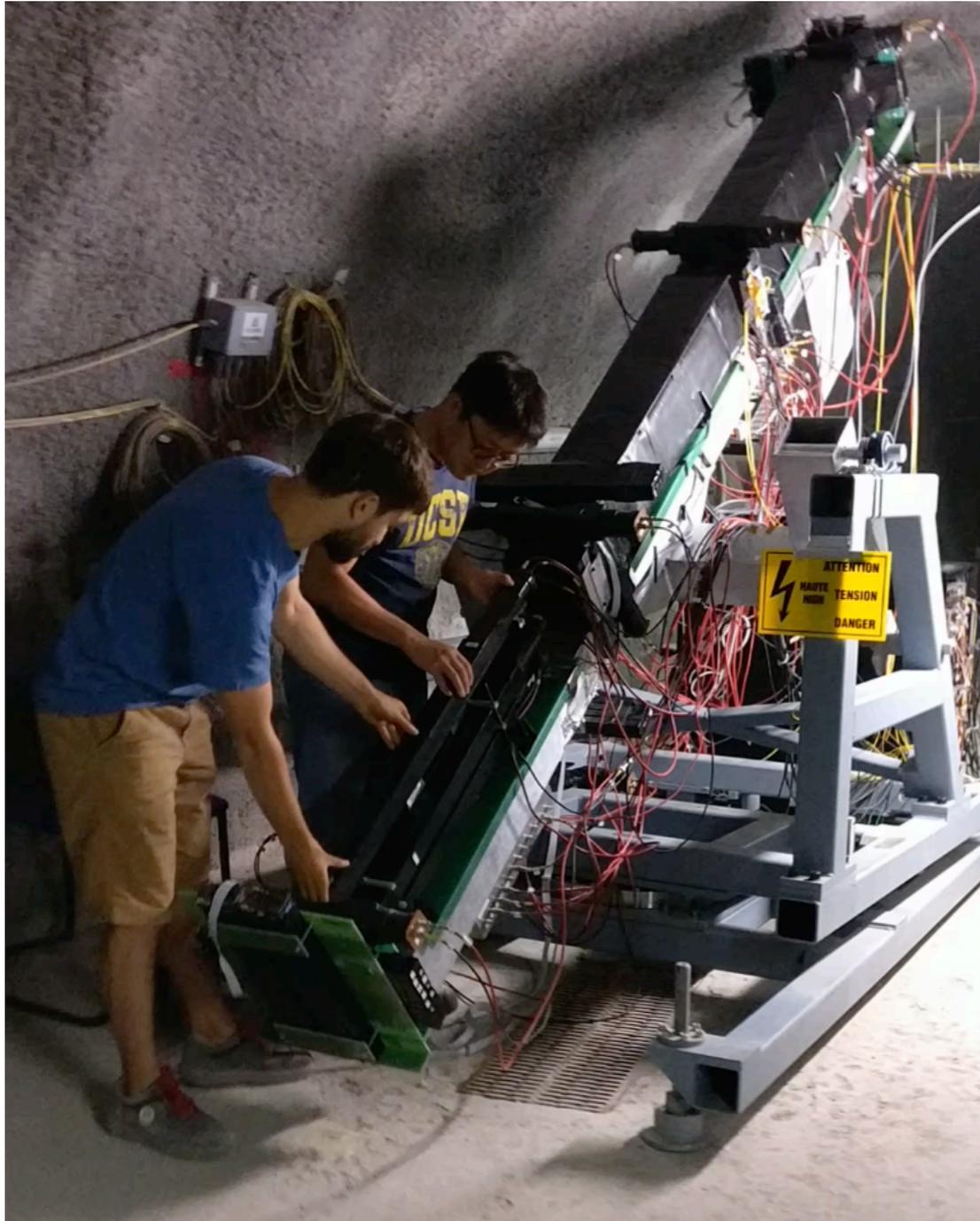
dual digitiser readout

CAEN V1743 digitizer:
16 chan, 1.6 GS/s,
640 ns window

- 3 layers of 2x3 scintillator+PMT
 - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
 - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
 - Tag cosmic muons
- Hodoscope packs
 - Track beam/cosmic muons
- Environmental sensors to measure humidity and magnetic field



Demonstrator



Installed on mount designed to hold full detector

- Ran very successfully, collecting **~35/fb, 2000h** of data in 2018
- Operational experience in difficult environment: triggering/DAQ/DQM
- Used for range of studies to prove feasibility of full detector: **alignment, calibrations, background measurements**
- Fully simulated in GEANT4 (validated in data)
- First search for millicharged particles at the LHC!

Calibrations

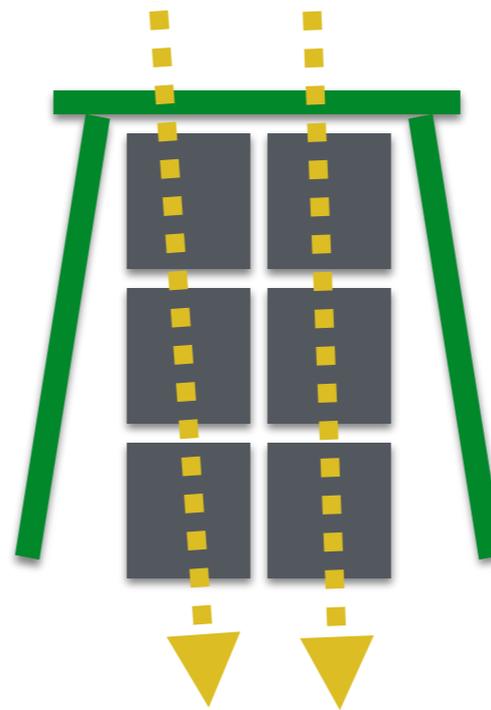
- In-situ charge calibration

- Calculate N_{PE} produced by a cosmic muon ($Q=1e$) per PMT and scale (Q^2)
- Find **$N_{PE} = 1$ for $Q \sim 0.003e$** \rightarrow consistent with result from full GEANT4 simulation used for LOI

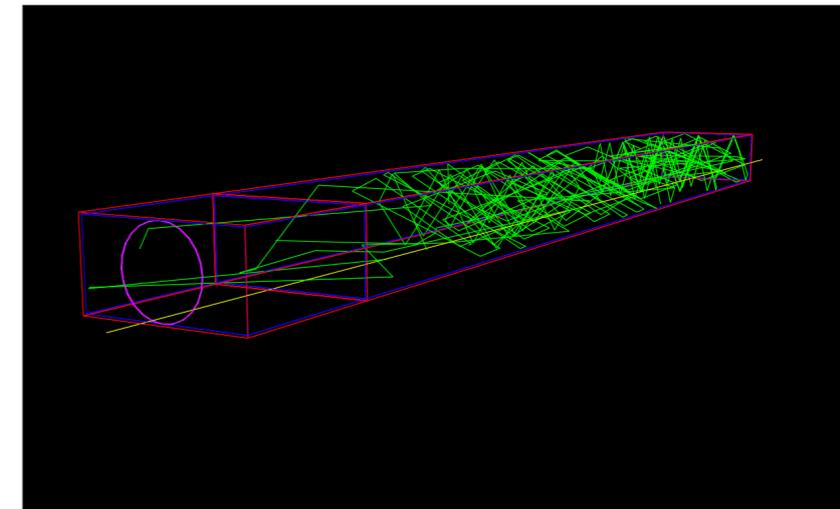
- Timing calibration

- Cable length, PMT rise time and geometric differences must be calibrated (done using beam/cosmic muons)
- Achieve ~ 4 ns resolution \rightarrow easily sufficient for 15 ns window between hits in layers

Downgoing cosmic
used for charge calibration

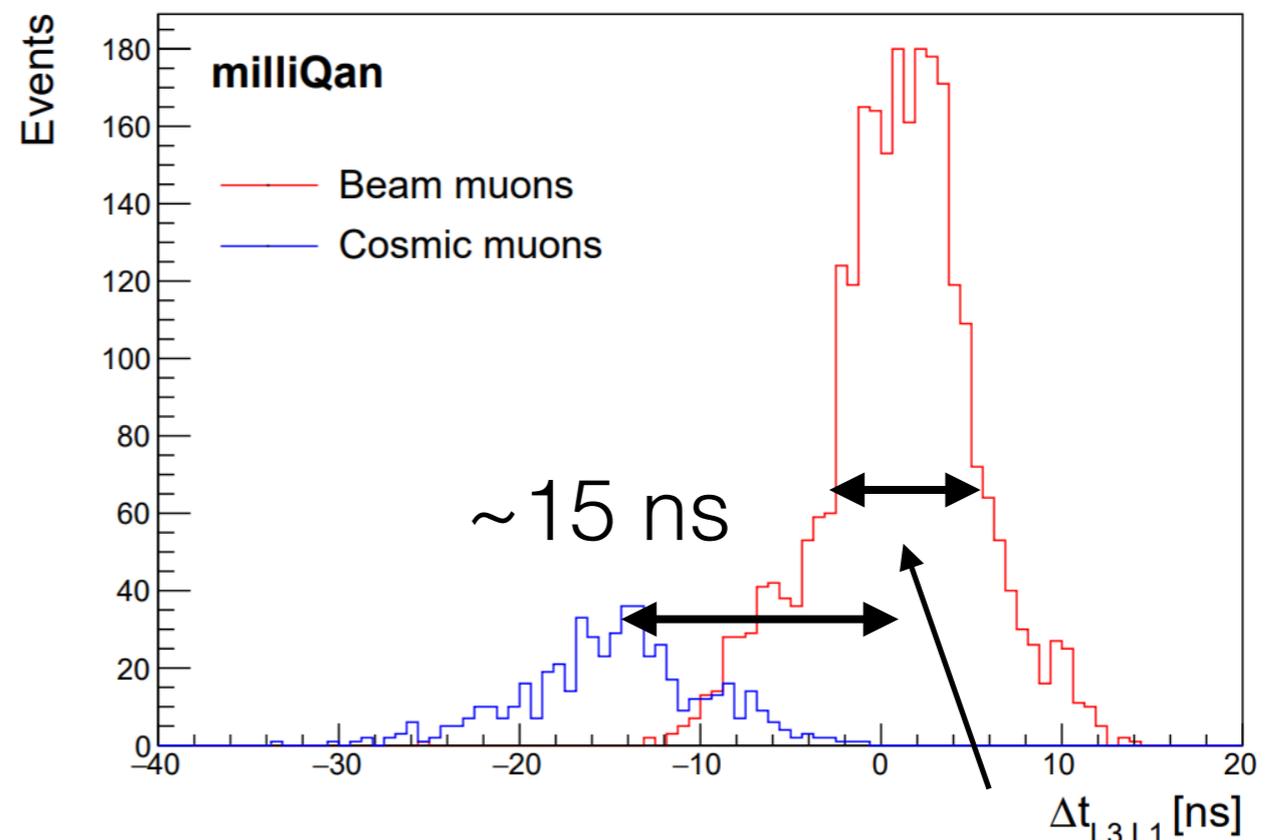


GEANT4 simulation



Calibrated time difference between L3 and L1

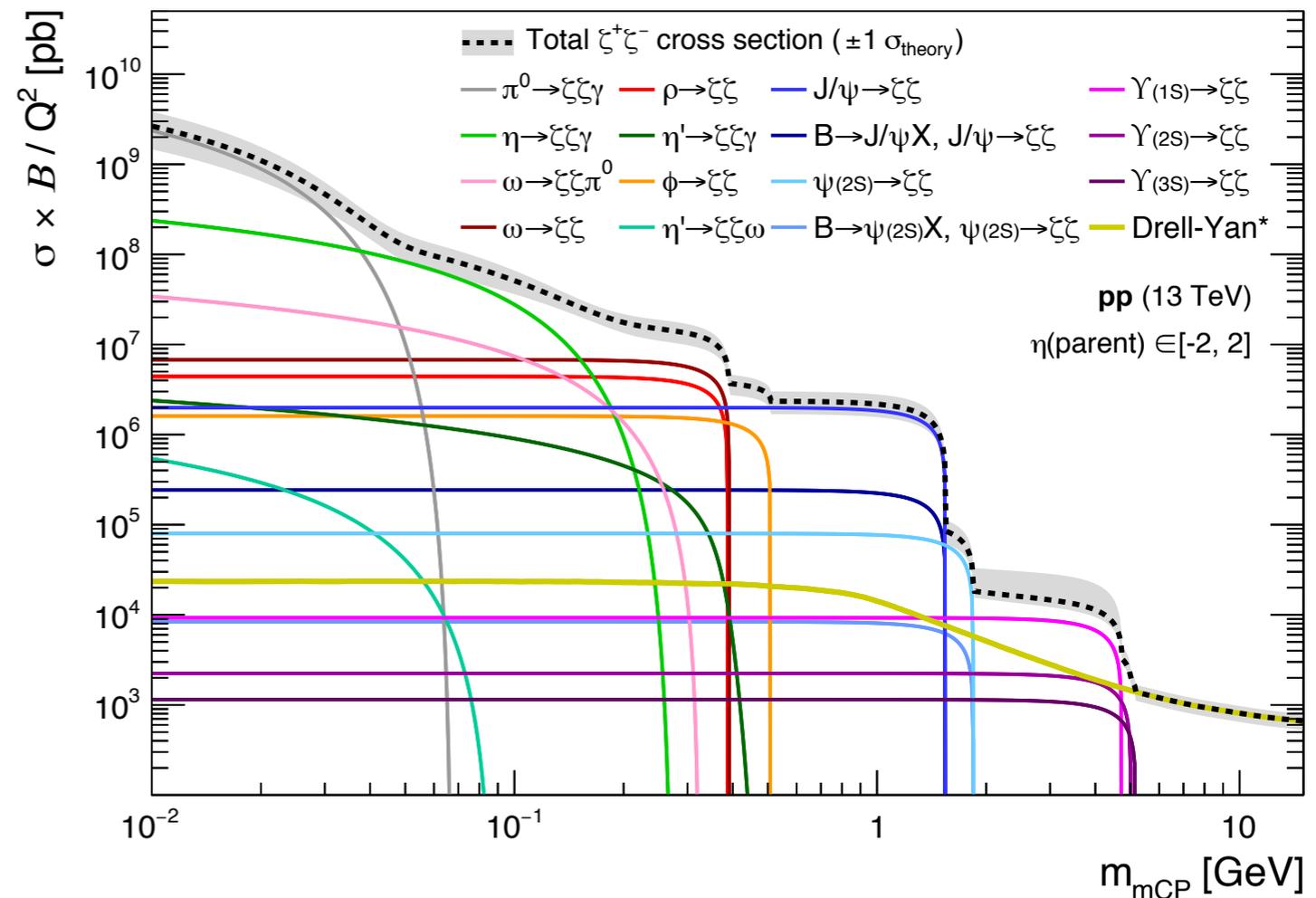
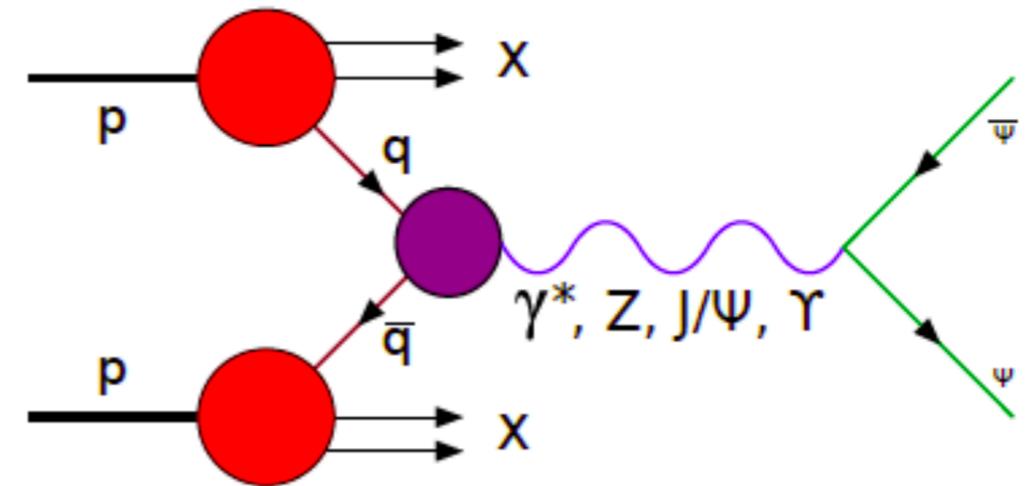
37.5 fb⁻¹



resolution ~ 4 ns

Simulation

- Signal: wide range of mCP production mechanisms considered!
- Propagate to detector considering **multiple scattering** and **CMS magnetic field**
- Passed to GEANT4 simulation 2m before detector face
- Background: generate and propagate muons produced in LHC collisions and cosmic muons from the surface
 - Used to validate simulation and characterise backgrounds
 - Interactions with the cavern and detector material are simulated in GEANT4



Simulation validation

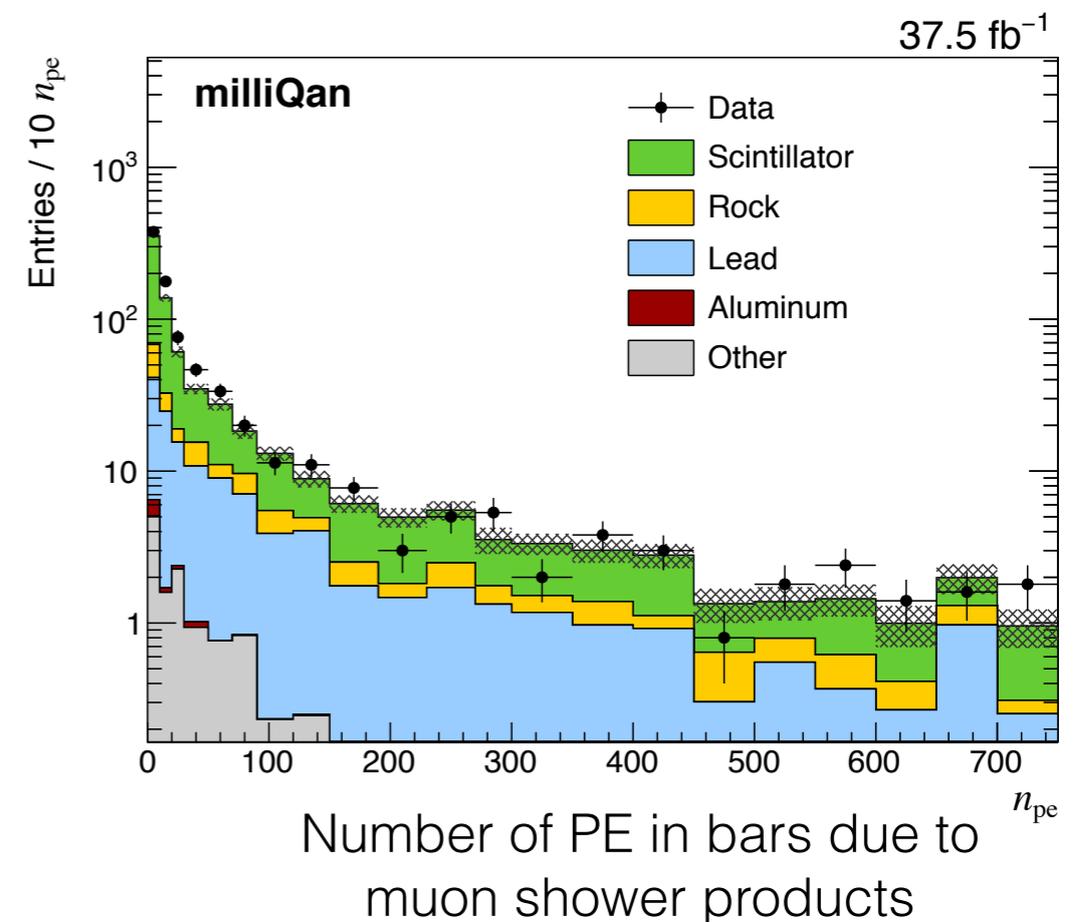
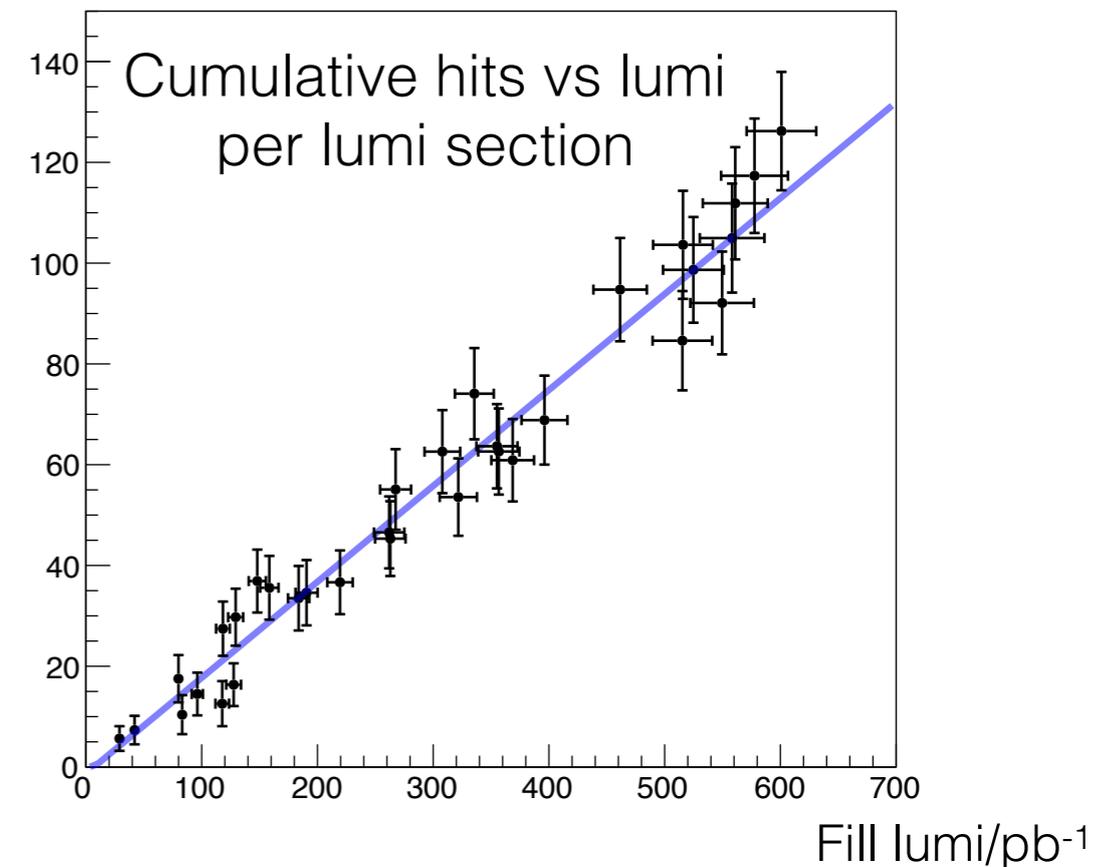
- **Generation and propagation**

- Check beam muon occupancy agrees with expectation
- Measured rate: **$0.20/\text{pb}^{-1}$** agrees well with expected rate: **$0.25 \pm 0.08/\text{pb}^{-1}$**
- Also validate angular spread of beam muons (see backup)

- **Detector response**

- Comparison of photon yields in data and simulation shows **good agreement** across a wide range of energy depositions

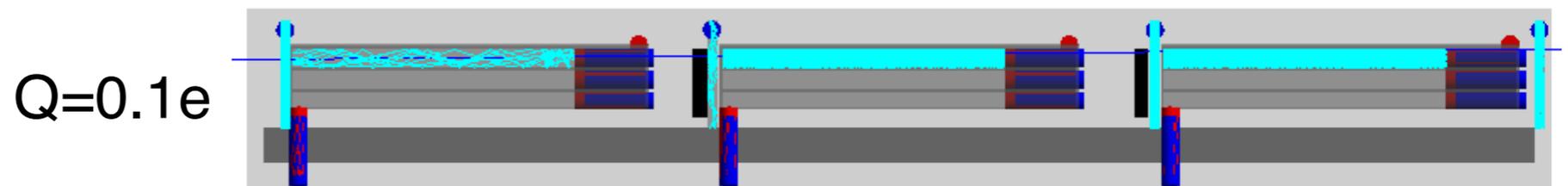
- Detector **calibrated** and simulation **validated** → search for millicharged particles!



Signal selection and categorisation

- Selections: event must have **exactly 3 hits**, **within 15ns**, in a **pointing path** (all with well-behaved signal amplitudes)
- Under these selections, backgrounds are reduced by **5 orders of magnitude**
- We **categorise** signal using # of PE and slab deposits to optimise sensitivity for a wide range of charges

Selection	Data	Data	Signal	Signal	Signal	
	Beam-on $t = 1106$ h	Beam-off $t = 1042$ h	$m_\chi = 0.05$ GeV $Q/e = 0.007$	$m_\chi = 1.0$ GeV $Q/e = 0.02$	$m_\chi = 3.0$ GeV $Q/e = 0.1$	
Common	> 1 hit per layer	2 003 170	1 939 900	136.4	34.2	5.7
Selections	Exactly 1 hit per layer	714 991	698 349	123.1	31.0	5.0
	Panel veto	647 936	632 494	122.5	30.8	4.9
	First pulse is max	418 711	409 296	114.3	30.6	4.8
	Veto early pulses	301 979	295 040	113.9	30.6	4.8
	$\max n_{pe} / \min n_{pe} < 10$	154 203	150 949	104.2	29.6	4.7
	$\Delta t_{\max} < 15$ ns	5 284	5 161	72.8	28.4	4.4
	Slab muon veto	5 224	5 153	72.8	28.4	4.4
	Straight path	350	361	68.4	28.1	4.2
	$N_{\text{slab}} = 0$	332	339	64.8	16.9	0.0
	$N_{\text{slab}} \geq 1$	18	22	3.6	11.2	4.2
SR 1	$N_{\text{slab}} = 0$ & $\min n_{pe} \in [2, 20]$	129	131	47.4	0.4	0.0
SR 2	$N_{\text{slab}} = 0$ & $\min n_{pe} > 20$	52	45	0.0	16.5	0.0
SR 3	$N_{\text{slab}} = 1$ & $\min n_{pe} \in [5, 30]$	8	9	1.1	0.5	0.0
SR 4	$N_{\text{slab}} = 1$ & $\min n_{pe} > 30$	4	4	0.0	8.7	0.0
SR 5	$N_{\text{slab}} \geq 2$	1	1	0.0	2.0	4.2



Sample through-going mCP

Background prediction

- Background predicted using ABCD method inverting **timing** and **pointing path** requirements in beam-on dataset (details in backup)
- Beam does not contribute to background (confirmed from simulation and data) → validate prediction method using beam-off dataset
- Agreement in validation check defines systematic uncertainty

Signal region predictions and observations

Region	N_{slab}	min n_{pe}	Prediction	Observation
1	0	[2,20]	124_{-11}^{+11}	129
2	0	> 20	$49.9_{-5.4}^{+6.0}$	52
3	1	[5,30]	$10.7_{-2.6}^{+3.6}$	8
4	1	> 30	$2.4_{-1.1}^{+2.1}$	4
5	≥ 2	-	$0.0_{-0.0}^{+0.9}$	1

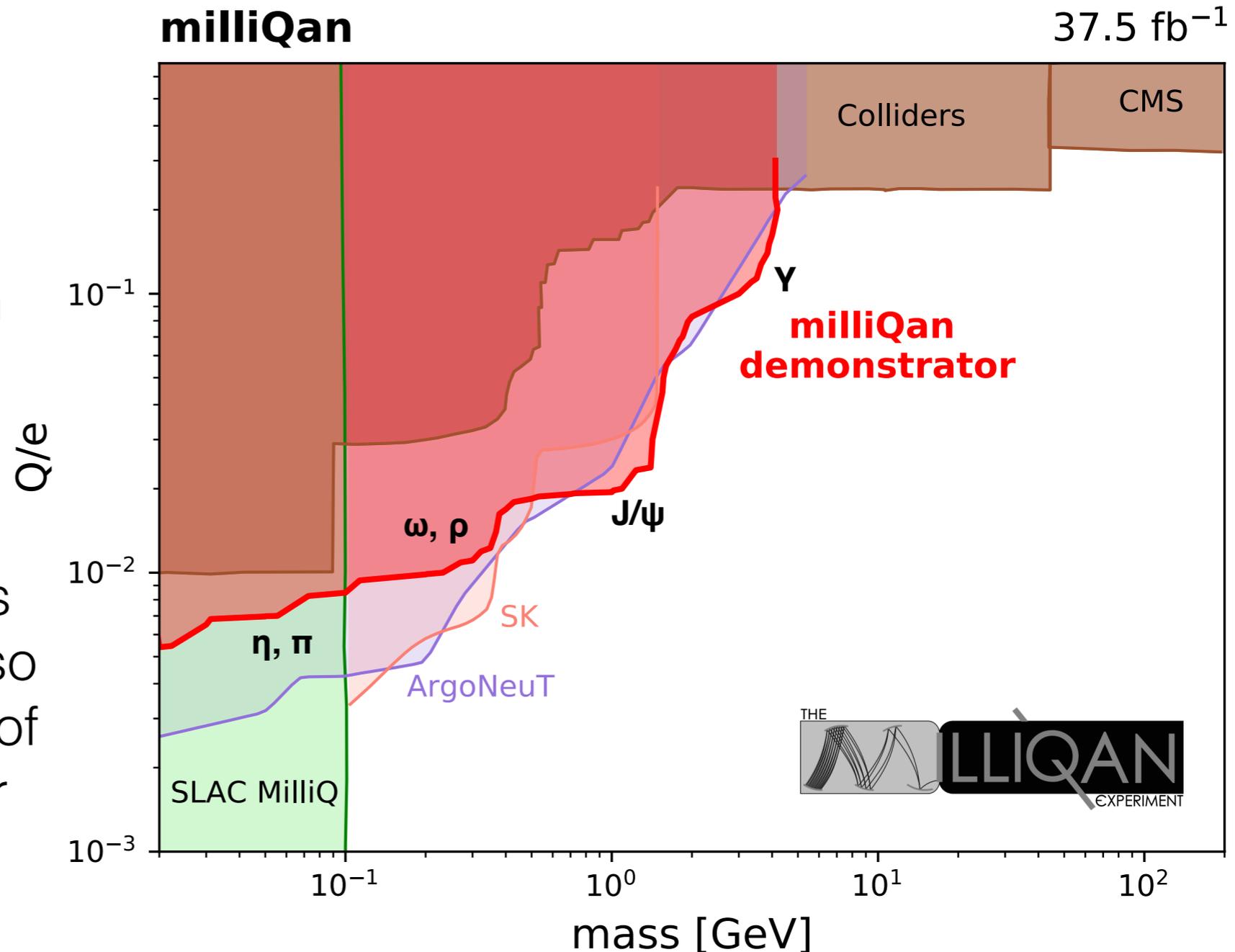
Good agreement with prediction in all SRs → derive exclusion limits on mCP mass/charge

Search results

The 1% milliQan demonstrator achieves **competitive constraints** on mCPs with mass < 4.7 GeV

The demonstrator provides new exclusion limits, but also quantitative understanding of backgrounds and detector performance

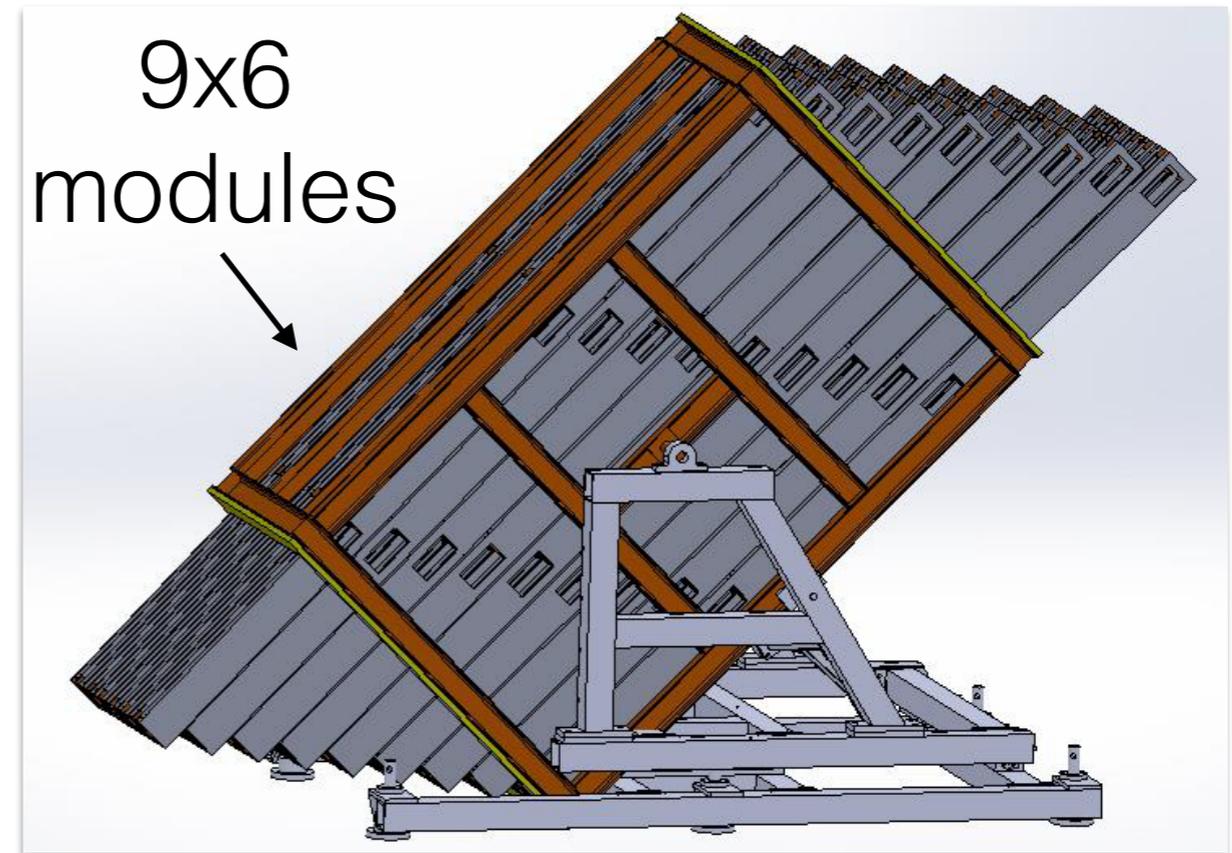
→ **Using experience to guide future detector!**



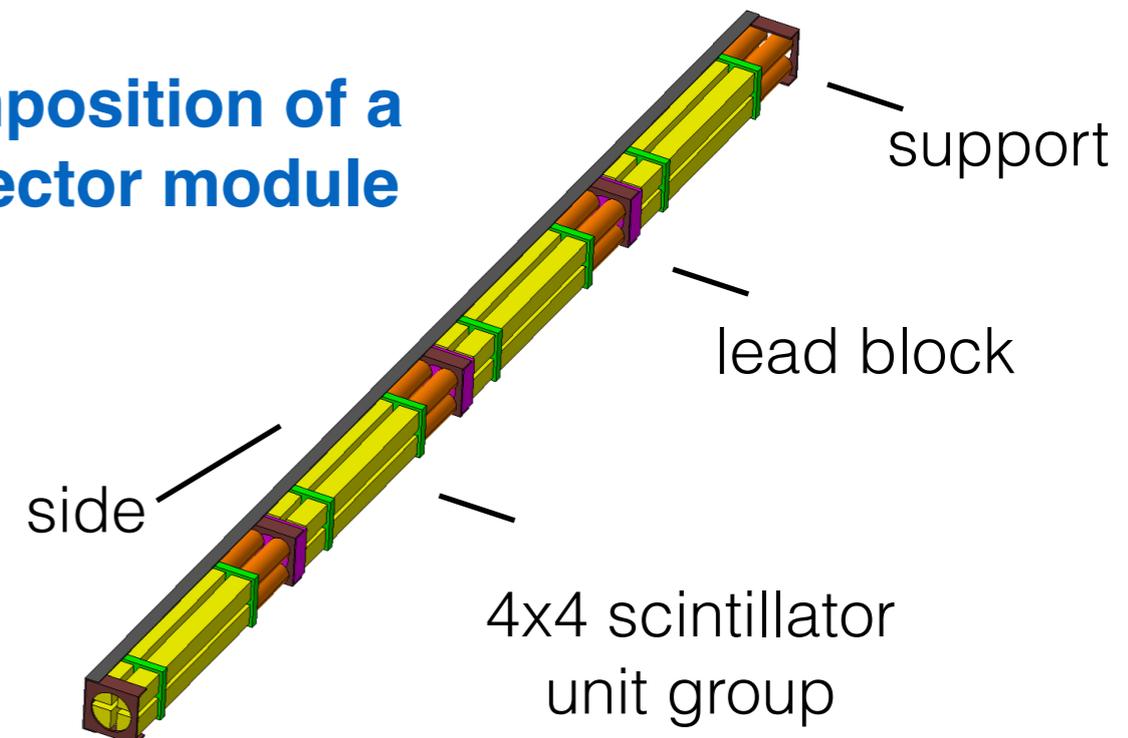
Accepted in PRD:
[arXiv:2005.06518](https://arxiv.org/abs/2005.06518)

Next step: build full detector

- Plans for mechanical structure finalised: two adjacent detectors of 864 bars in four layer configuration
- Updated projections with robust background predictions to be provided in upcoming paper
- Better PMTs, additional layer and larger active veto volume will provide **leading sensitivity** for mCPs from < 1 GeV to at least $M_Z/2$ (~ 45 GeV)
- Exciting prospects at low mass for similar detectors at DUNE/J-PARC



Composition of a detector module



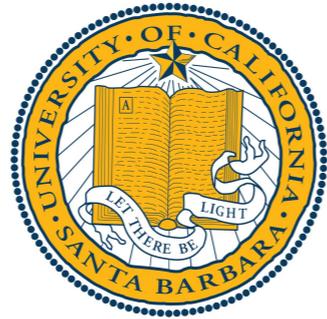
Conclusions

- The milliQan detector can provide **unique sensitivity** to millicharged particles
- Built, commissioned and operated small prototype to **prove feasibility** and **measure backgrounds** rate for full detector
- Signal generation, propagation and detector response **fully simulated**
- Search for millicharge particles with prototype achieves **competitive constraints**
- **Mature mechanical** design for full detector - **actively seeking funding to install detector** for upcoming runs of the LHC

milliQan collaboration



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milliQan demonstrator search results paper available now on arXiv, accepted by PRD

Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV

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 (Dated: May 15, 2020)

We report on a search for elementary particles with charges much smaller than the electron charge using a data sample of proton-proton collisions provided by the CERN Large Hadron Collider in 2018, corresponding to an integrated luminosity of 37.5 fb^{-1} at a center-of-mass energy of 13 TeV. A prototype scintillator-based detector is deployed to conduct the first search at a hadron collider sensitive to particles with charges $\leq 0.1e$. The existence of new particles with masses between 20 and 4700 MeV is excluded at 95% confidence level for charges between 0.006e and 0.3e, depending on their mass. New sensitivity is achieved for masses larger than 700 MeV.

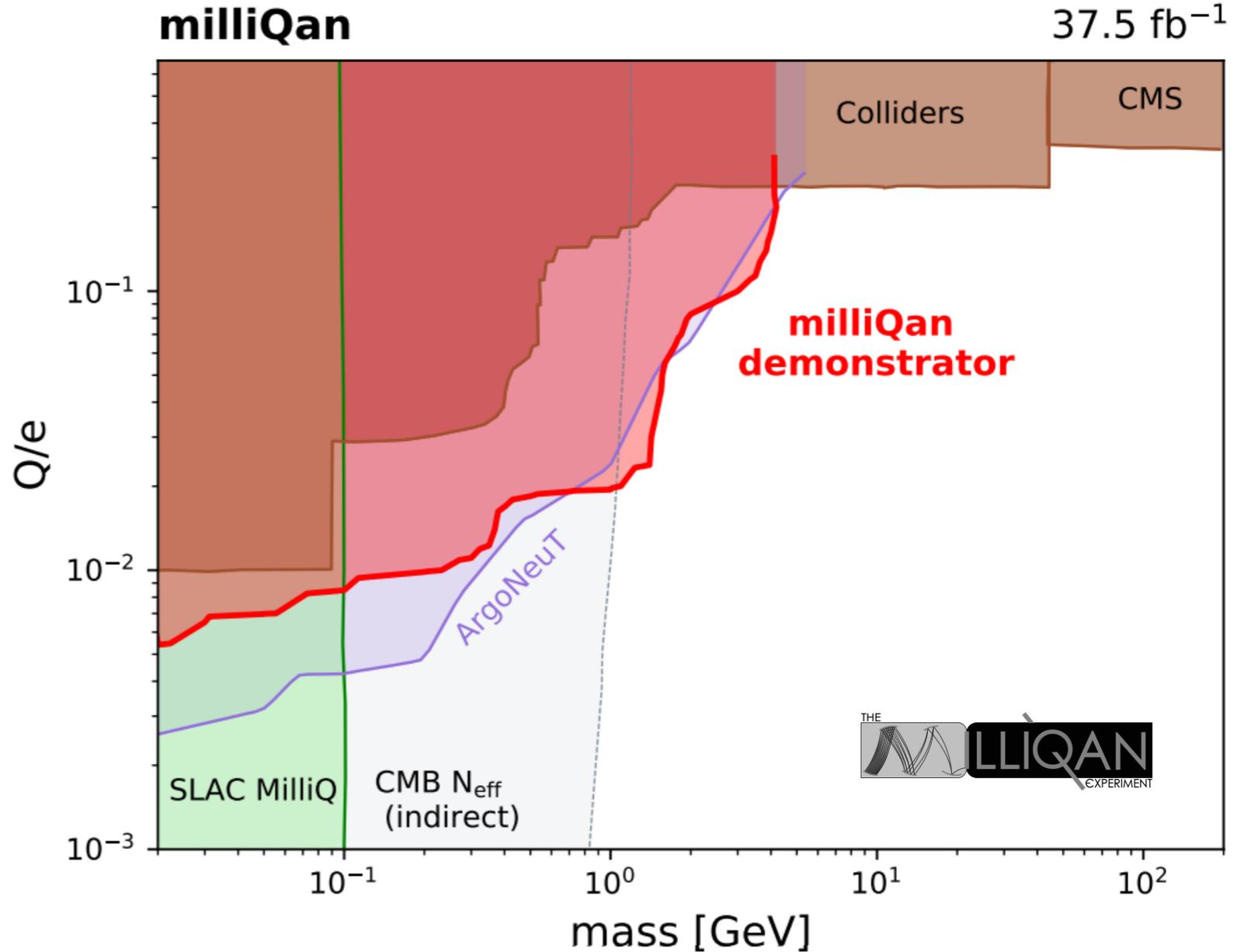
I. INTRODUCTION

Over a quarter of the mass-energy of the Universe is widely thought to be some kind of nonluminous “dark” matter (DM), however, all experiments to date have failed to confirm its existence as a particle, much less its properties. The possibility that DM is not a single particle, but rather a diverse set of particles with as complex a structure in their sector as normal matter, has grown in prominence in the past decade, beginning with attempts to explain observations in high-energy astrophysics experiments [1, 2].

Many experimental efforts have been launched to look for signs of a dark sector, including searches at high-energy colliders, explorations at low-energy colliders, precision tests, and effects in DM direct detection experiments (for recent reviews see Refs. [3–5]). Most of these experiments target the dark sector via a massive dark photon, in what we refer to as the “Okun phase” [6, 7]. An alternative assumption, which we call the “Holdom phase” [8, 9], results in massless dark photons. In these models the principal physical effect is that new dark sector particles that couple to the dark photon will have

a small effective electric charge. These are generically called millicharged particles since a natural value for their electric charge of $Q \sim \alpha e/\pi$ arises from one-loop effects [10]. In this paper we use the symbol χ to denote a millicharged particle. For a given mass and charge, the pair production of millicharged particles at the CERN Large Hadron Collider (LHC) is almost model independent. Every standard model (SM) process that results in dilepton pairs through a virtual photon would, if kinematically allowed, also produce $\chi^+\chi^-$ pairs with a cross section reduced by a factor of $(Q/e)^2$ and by mass-dependent factors that are well understood. Millicharged particles can also be produced through Z boson couplings that depend on their hypercharge [11].

Previous experiments have searched for millicharged particles [12–16]. The parameter space spanned by the mass and charge of χ is also constrained by indirect observations from astrophysical systems [9, 13, 17, 21], the cosmic microwave background (CMB) [21], big-bang nucleosynthesis [22], and universe overclosure bounds [17]. While direct searches robustly constrain the parameter space of millicharged particles, indirect observations can be evaded by adding extra degrees of freedom, which can readily occur in minimally extended dark sector models [1]. In particular, the parameter space $1 < m_\chi < 100 \text{ GeV}$, an ideal mass range for production at the LHC, is largely unexplored by direct (or indirect) searches. Such a signature would not be detectable by the CMS and ATLAS experiments at the LHC [23, 24], as all detector elements rely on the electromagnetic (EM) interaction of the millicharged particle with ordinary matter. For a



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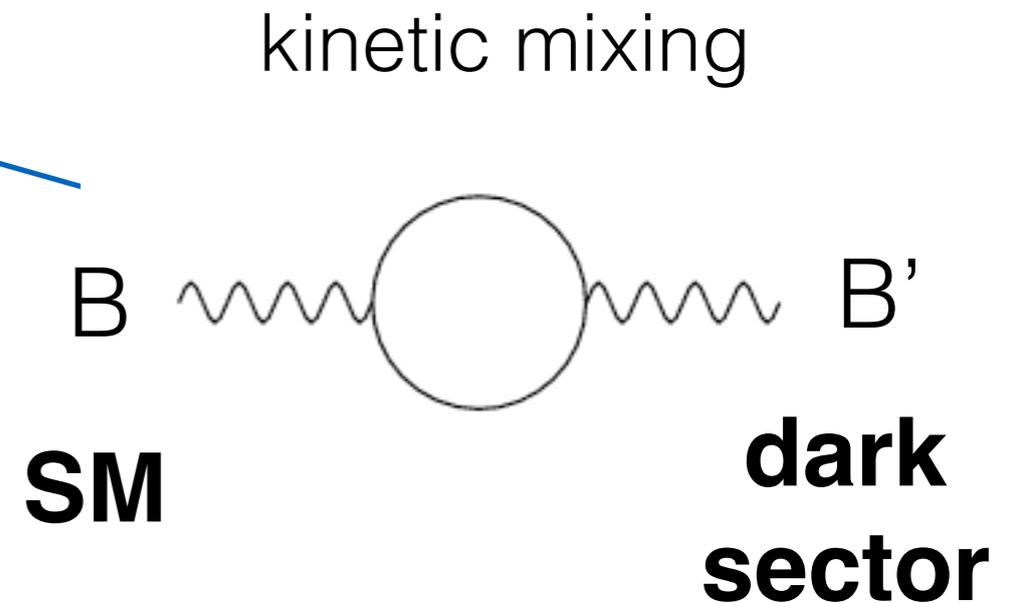
Backup

Why milli-charged?

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu}$$

massless U'(1) boson in the dark sector

'dark EM'



$$\kappa \sim 10^{-3} - 10^{-2}$$

(naturally $\sim \alpha/\pi$)

Kinetic mixing with a new massless 'dark' boson **can provide link between SM and a hidden/dark sector**

Why milli-charged?

Now add fermion charged under new $U'(1)$:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie'\not{B}' + iM_{mCP})\psi$$

Standard trick - redefine gauge field B' : $B' \rightarrow B' + \kappa B$

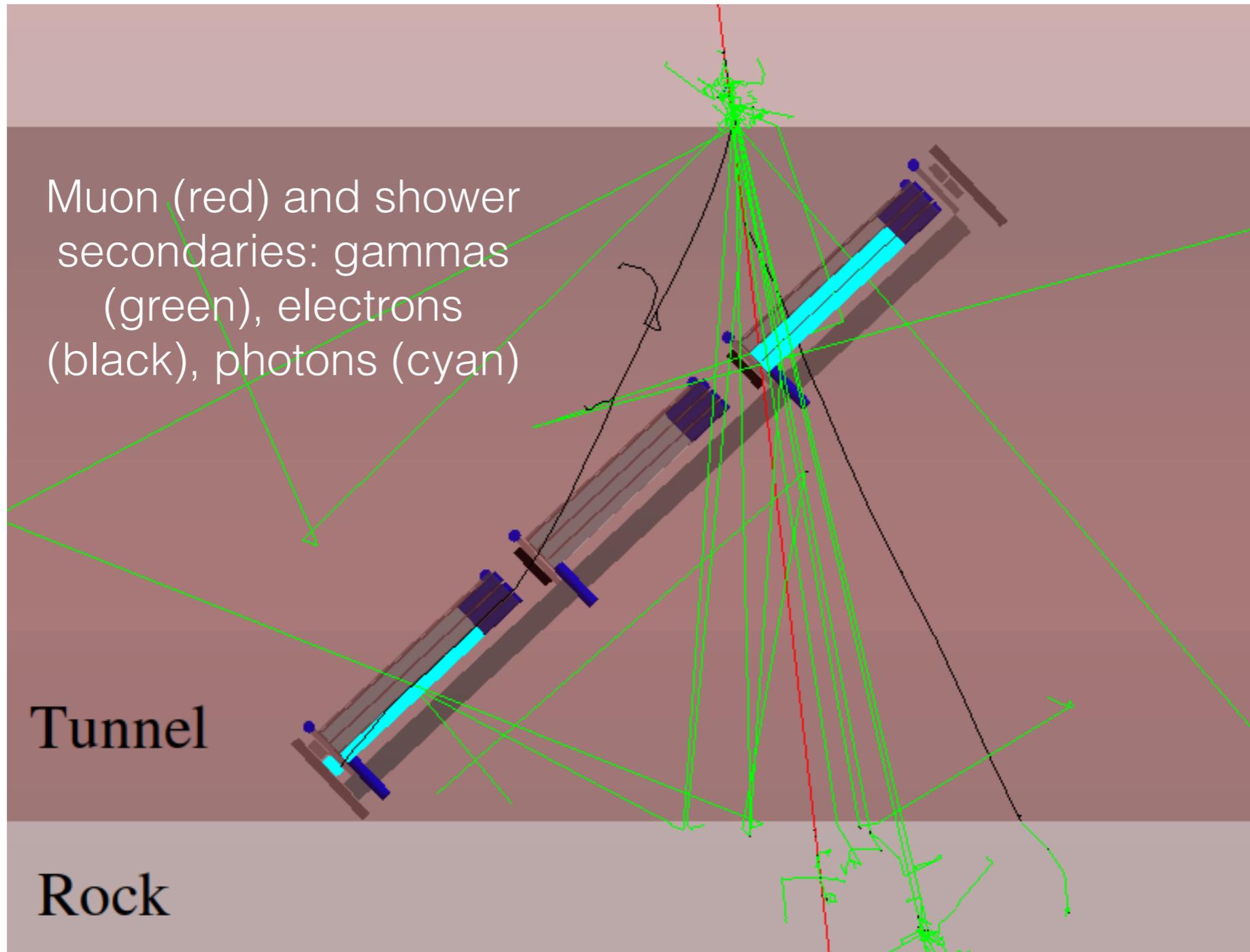
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + i\bar{\psi}(\not{\partial} + \underbrace{ike'\not{B}} + ie'\not{B}' + iM_{mCP})\psi$$

new fermion has small EM charge: **milli-charged particle**

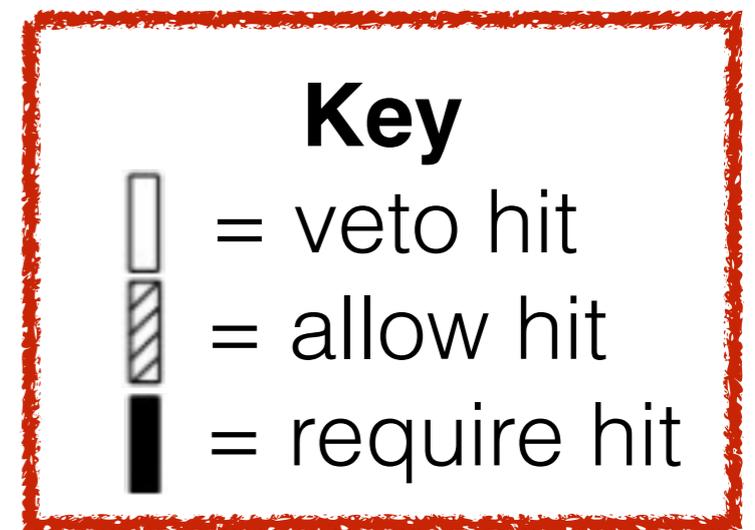
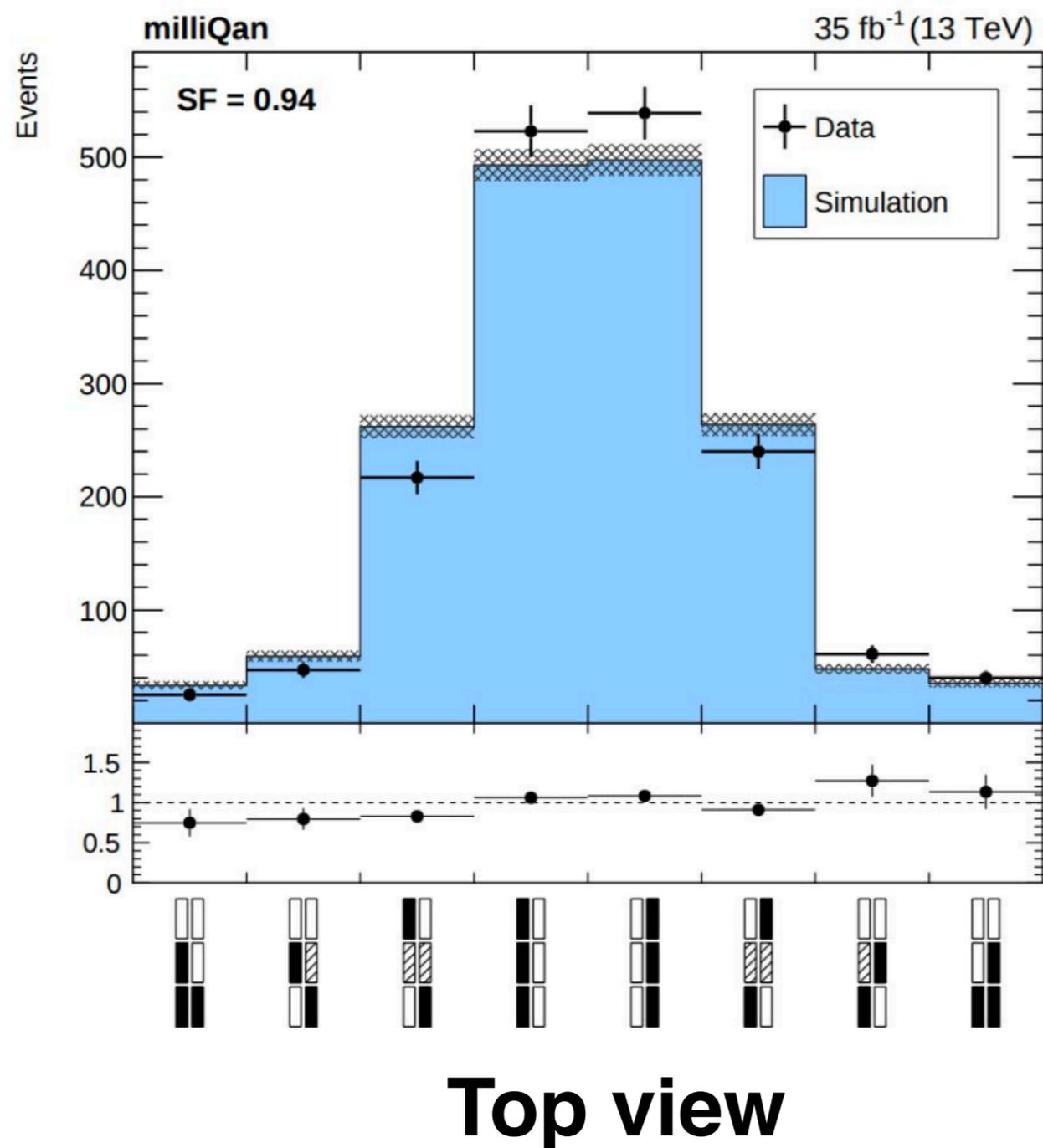
Background Sources

- The following components potentially contribute to background:
 - **PMT Dark Counts**: overlap of dark rate from three in-line PMTs, or one PMT and two correlated background hits
 - **Cosmic and beam muon shower secondaries**, especially electrons and gammas, can cause a pulse in each layer of the demonstrator
 - **Radiation** from the cavern, bars, or surrounding material (mostly Pb shielded)
 - **Afterpulses**: Small, delayed pulses in PMTs caused by ionization of residual gases following an initial detection
- A detailed detector simulation allows us to **understand these sources in detail**

Example cosmic shower event



Validate angular description using paths through detector



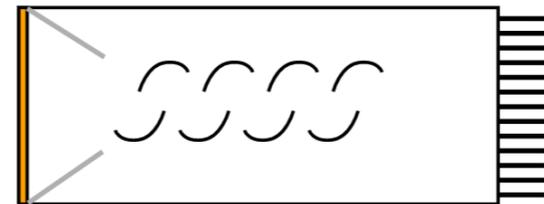
Angular spread through demonstrator well described by simulation!

In-situ charge calibration

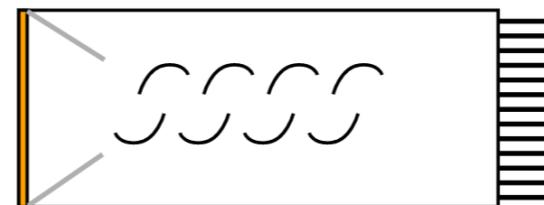
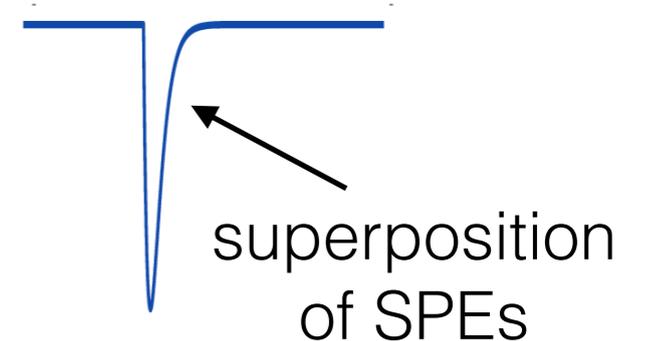
$Q = 1 \rightarrow$ many scintillation photons A

scales as Q^2

$Q \ll 1 \rightarrow$ few/ single photon(s) B

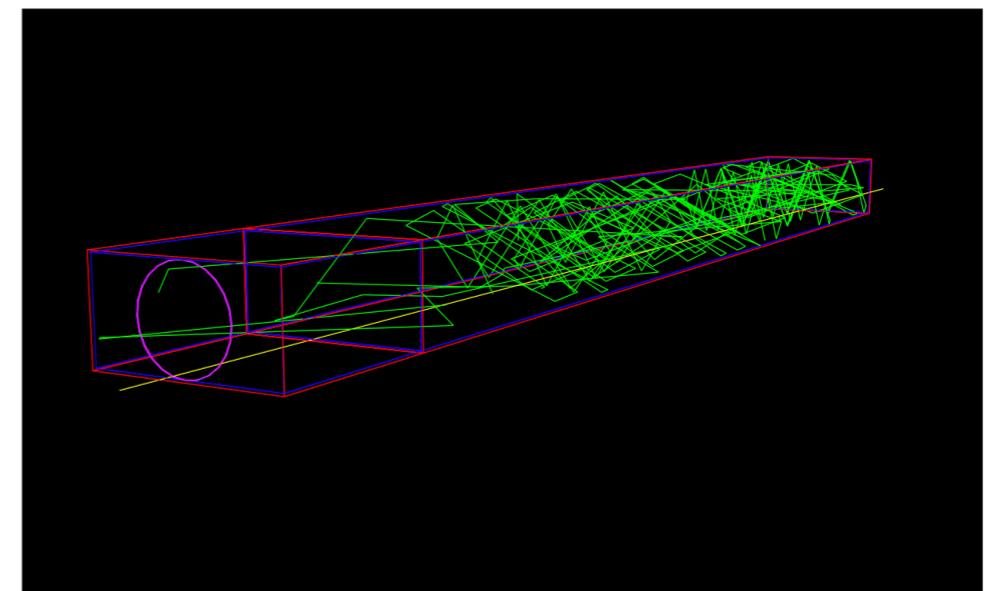


Waveform output



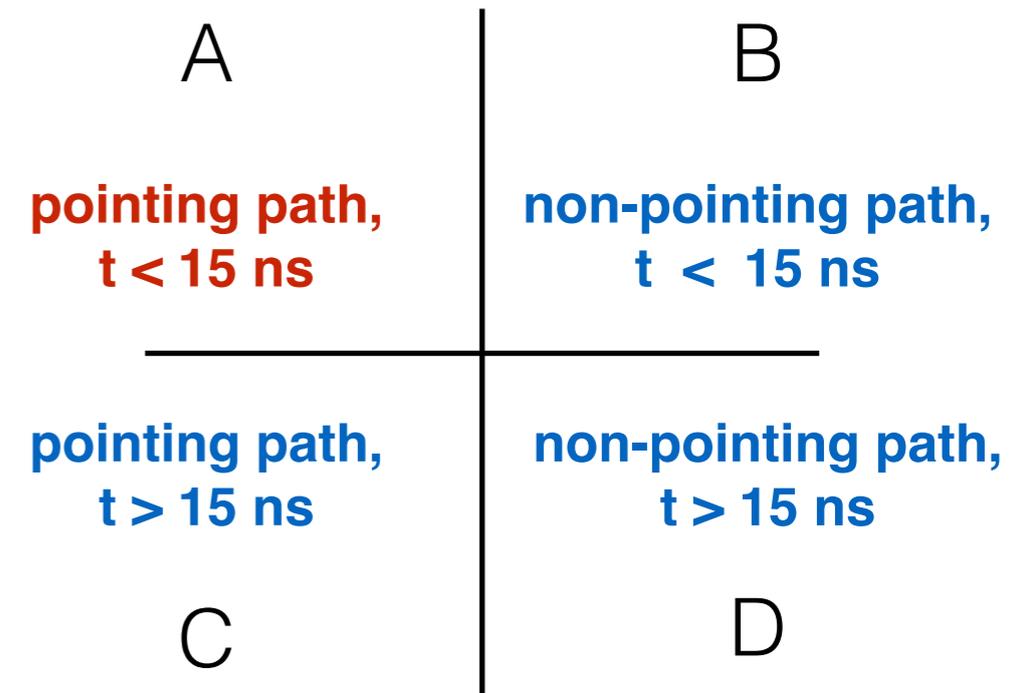
Carlos Hernandez Faham

- Need to know number of photons (N_{PE}) produced for a given Q
- Calculate N_{PE} produced by a cosmic muon ($Q=1e$) and scale (Q^2)
- $N_{PE}(Q=1e) = \text{pulse area (cosmic)}/\text{pulse area single photon (SPE)}$
- Find **$N_{PE} = 1$ for $Q \sim 0.003e$** \rightarrow consistent with result from full GEANT4 simulation



Predictions and validation

- Predictions generated using ABCD method inverting timing and geometric requirements in beam on data
- Beam does not contribute to background (confirmed from simulation and data), so we validate using beam off data below



Background vs. Prediction (beam off)

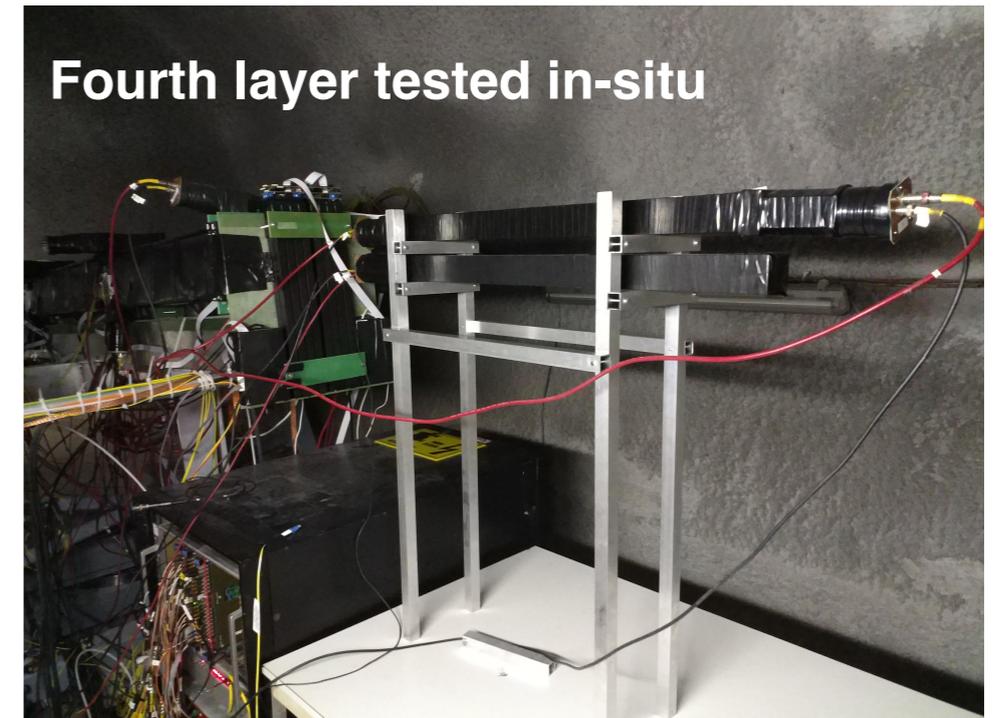
Region	N_{slab}	min n_{pe}	Prediction	Observation	Systematic
1	0	[2,20]	$121.2^{+6.0}_{-5.9}$	131	8%
2	0	> 20	$47.4^{+5.2}_{-4.8}$	45	5%
3	1	[5,30]	$7.8^{+2.5}_{-1.8}$	9	15%
4	1	> 30	$2.7^{+2.1}_{-1.1}$	4	48%
5	≥ 2	-	$0.8^{+1.4}_{-0.4}$	1	25%

Use agreement between prediction and background to derive systematics

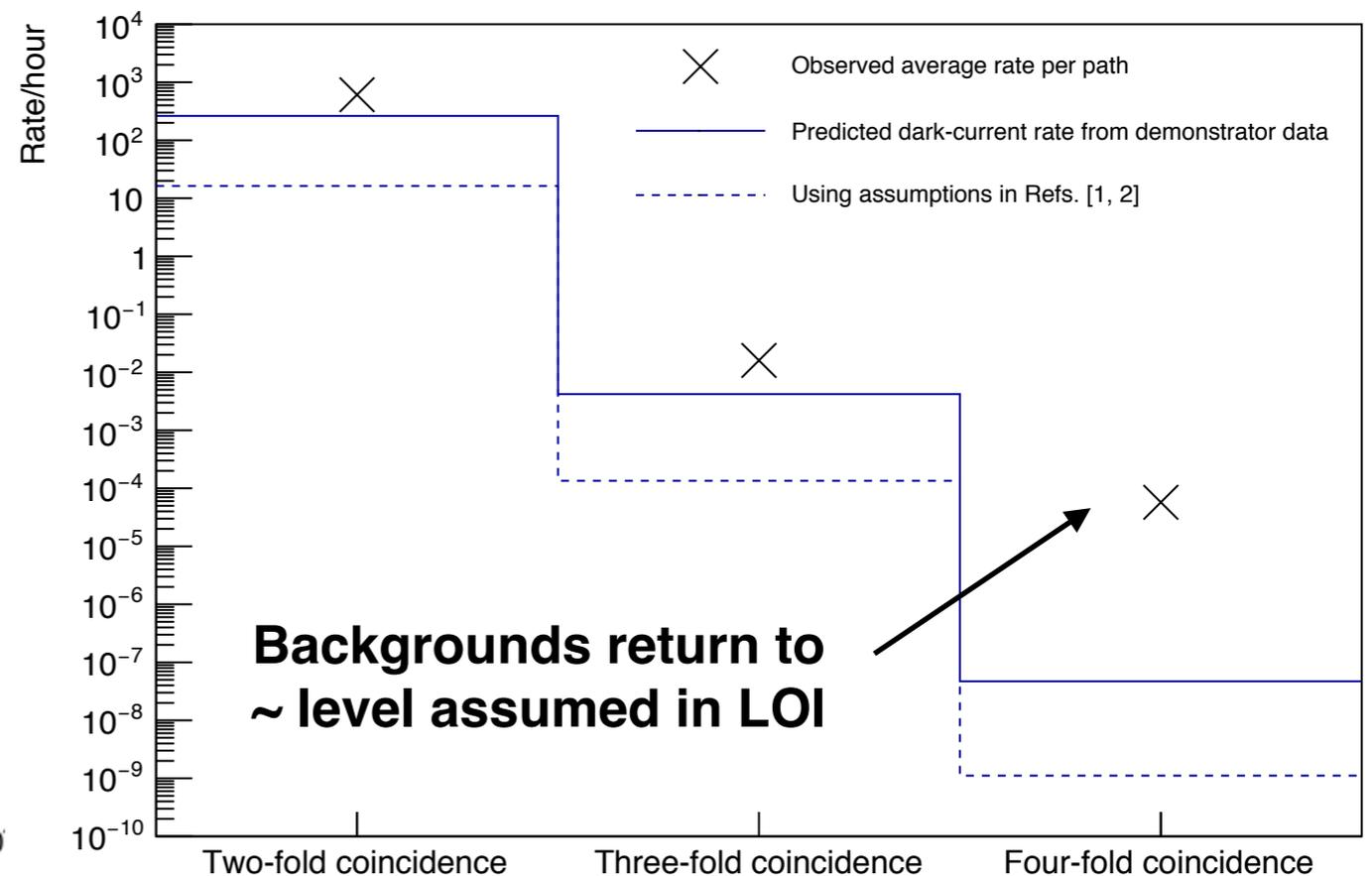
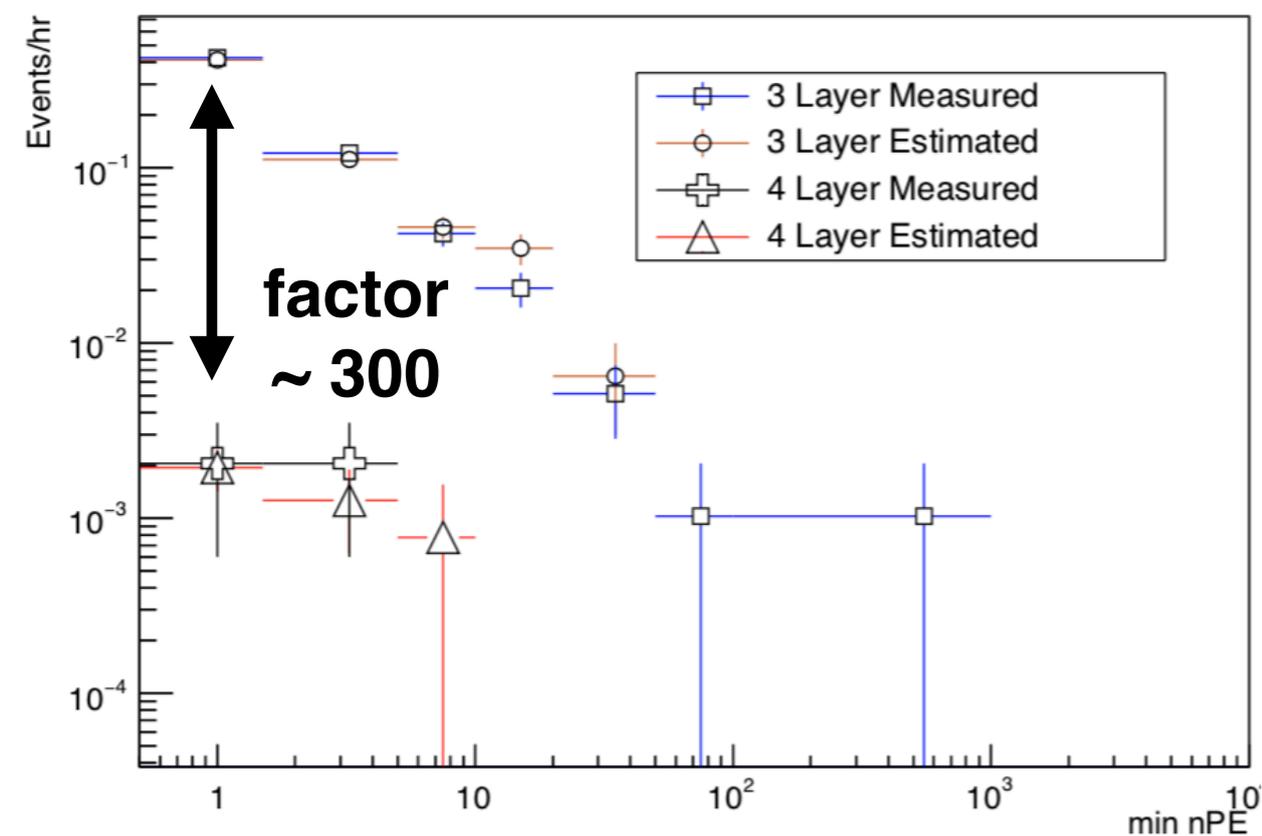
1042 hr beam off data collected

Background measurement

- Detector **aligned** and **calibrated** - measure backgrounds for full milliQan detector
- Major lesson from demonstrator: dark rate subdominant background source
- Motivates update to 'four layer' design → achieve targeted background rate

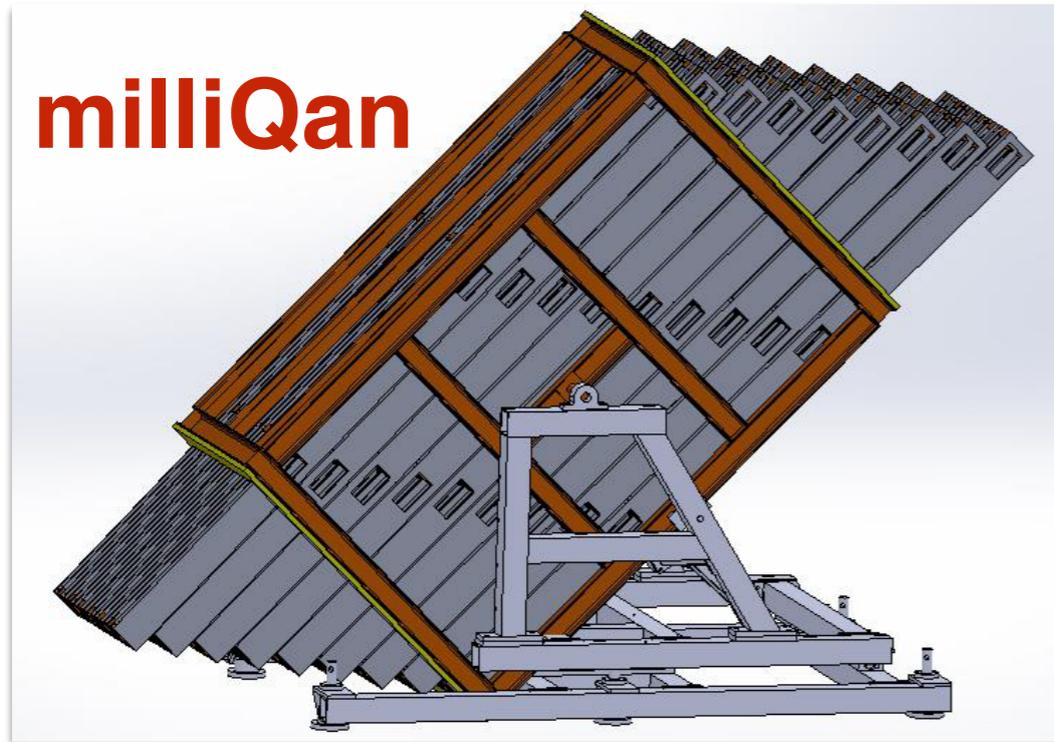


3 Layer v. 4 Layer Closure Test



Signal selection: coincident hits within 15 ns (pointing to IP)

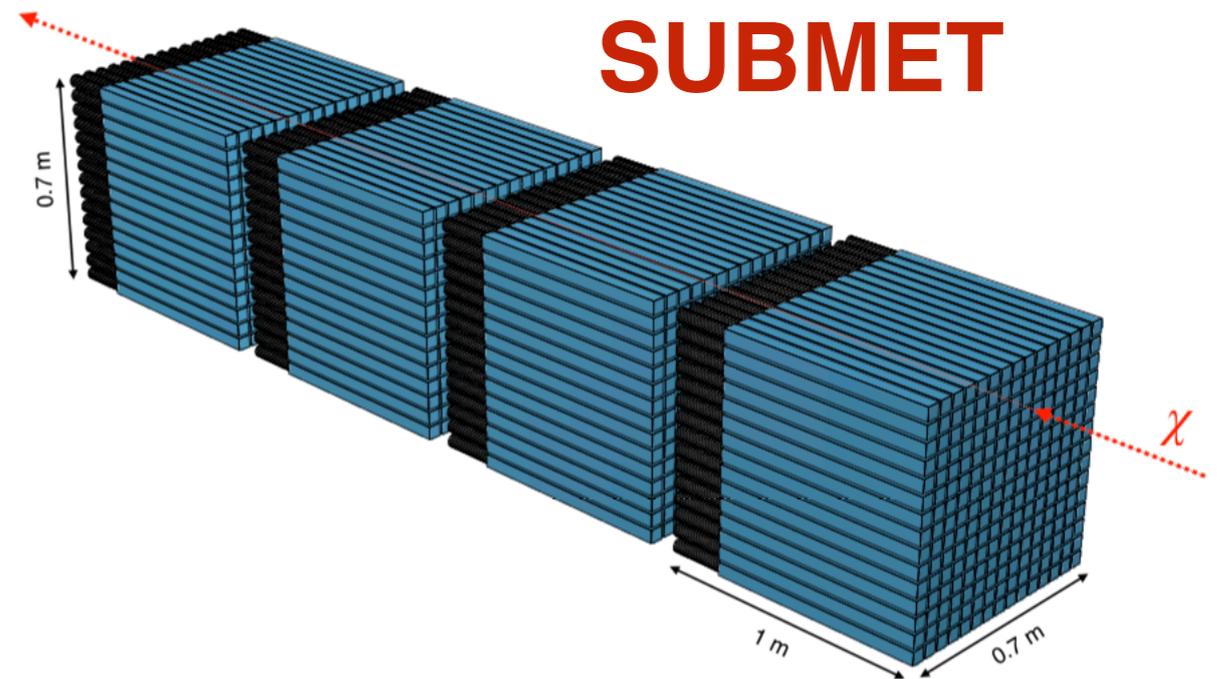
Scintillation based detection



milliQan

LHC with sensitivity for $m < \sim 45$ GeV

1607.04669

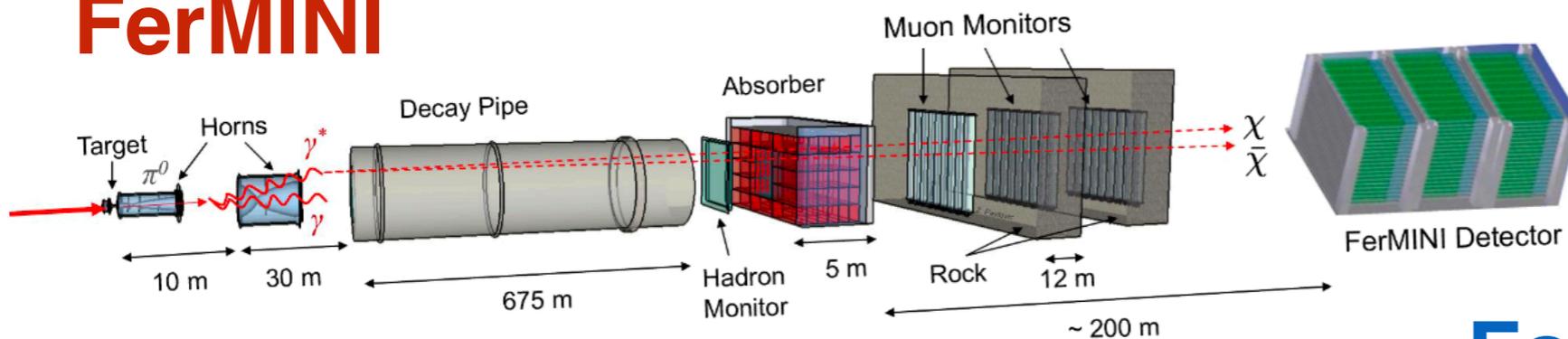


SUBMET

J-PARC with sensitivity for $m < \sim 1.5$ GeV

2007.06329

FerMINI



Fermilab with sensitivity for $m < \sim 5$ GeV

1812.03998

Range of detectors with complementary sensitivity

For milliQan: proof of concept “demonstrator” installed at CERN

Current projections

